八、2010年度新入选优秀青年学者

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Single-Molecule Chemistry of Metal Phthalocyanine on Noble Metal Surfaces

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CONCEPTUS

To develop new functional materials and nanoscale electronics, researchers would like to accurately describe and precisely control the quantum state of a single molecule on a surface. Scanning tunneling microscopy (STM), combined with first-principles simulations, provides a powerful technique for acquiring this level of understanding. Traditionally, metal phthalocyanine (MPC) molecules, composed of a metal atom surrounded by a ligand ring, have been used as dyes and pigments. Recently, MPC molecules have shown great promise as components of light-emitting diodes, field-effect transistors, photovoltaic cells, and single-molecule devices. In this Account, we describe recent research on the characterization and control of adsorption and electronic states of a single MPC molecule on noble metal surfaces.

In general, the electronic and magnetic properties of a MPC molecule largely depend on the type of metal ion within the phthalocyanine ligand and the type of surface on which the molecule is adsorbed. However, with the STM technique, we can use on-site molecular “surgery” to manipulate the structure and the properties of the molecule. For example, STM can induce a dehydrogenation reaction of the MPC, which allows us to control the Kondo effect, which describes the spin polarization of the molecule and its interaction with the complex environment. A specially designed STM tip can allow researchers to detect certain molecule–surface hybrid states that are not accessible by other techniques. By matching the local orbital symmetry of the STM tip and the molecule, we can generate the negative differential resistance effect in the formed molecular junction. This orbital symmetry-based mechanism is extremely robust and does not critically depend on the geometry of the STM tip.

In summary, this simple model system, a MPC molecule adsorbed on a noble metal surface, demonstrates the power of STM for quantum characterization and manipulation of single molecules, highlighting the potential of this technique in a variety of applications.

Introduction

Molecular adsorption on surfaces is an important issue in fundamental physical science, and it is also significant for various applications in new industries, such as heterogeneous catalysis and nanoelectronics. In recent years, rapid progress in nanotechnology has drastically enhanced our capability to explore surface adsorption systems at the single-molecule level. Metal phthalocyanine (MPC) molecules, traditionally used as dyes and pigments, are composed of a metal atom and a surrounding ligand ring (Figure 1). Recently, it was shown that MPC also has great potential in applications such as light-emitting diodes,1 field-effect transistors,2 photovoltaic cells,3 and single-molecule devices.4–9 Due to their versatility for various applications, MPC molecules have become a model system for surface chemistry and nanotechnology.4–12

MPC provides a relatively standard and stable chemical environment for the central metal atom. When it is adsorbed onto the surface, the metal–ligand interaction and molecule–surface interaction are the two most important parameters to determine various physical and chemical properties of this adsorption system. Delicate molecule–surface coupling states have been
observed for a CoPc on the Au(111) surface. Combination of different metal atoms in MPC and different surfaces will lead to very different geometrical, electronic, and magnetic properties.

Scanning tunneling microscopy (STM) is a powerful tool for surface science. With an ideally sharp tip, STM can obtain a two-dimensional surface image corresponding to local density of states (LDOS) of the sample surface near the Fermi energy ($E_F$). On the other hand, if the coordinate of the STM tip on the sample surface is kept and the applied voltage is varied, a current–voltage ($I$–$V$) curve, also known as scanning tunneling spectrum (STS), can be obtained. Its differential $dI/dV$ spectrum roughly represents the relationship between the density of state (DOS) and the energy. In other words, information for both spatially and energetically resolved DOS can be revealed by a real space STM $dI/dV$ mapping technique. Since STM probes the electronic structure instead of atomic structure of the sample, theoretical simulation based on density functional theory (DFT) becomes a necessary tool to interpret and predict STM experimental observations.

STM has been utilized by many groups to study MPC adsorbed surfaces. More importantly, STM allows us to distinguish between the different metal atoms that are well characterized by STM. More importantly, it has been shown that single molecule manipulation can be realized by STM, for instance, to restore the quenched magnetic moment in a CoPc adsorbed on a Au(111) surface. A specifically designed STM tip can also be used as an electrode of a molecular junction to realize various functions such as negative differential resistance.

It is very convenient in STM experiments to observe magnetic properties of adsorbed molecules by checking the possible Kondo effect in the STS spectrum. Kondo effect refers to the exchange interaction between localized spins and conduction electrons. Such an interaction could significantly modify the transport properties of the studied systems. Kondo effect was used to explain the resistance minimum in metal at low temperature caused by magnetic impurity scattering. Recently, Kondo effect in quantum dot or single-molecule systems has attracted increased interest. In such systems, a high-order virtual tunneling process may effectively flip the spin on the quantum dot or molecule. Successive spin flips then screen the local spin and form an intermediate spin-singlet state between electrodes and quantum dot on short time scales. Due to the state, a peak appears in the tunneling density of states ($dI/dV$ spectrum) at the electrode Fermi level. This characteristic Kondo peak changes with temperature, and it typically can be fitted by the Fano model. Kondo temperature is an important parameter in the Fano model to describe the resonance width.

In this Account, we focus on interactions between MPC and the noble metal surface on which it adsorbs. Electronic structure engineering by changing substrate, central metal atom, and STM tip and also by STM manipulation is demonstrated. The related physical/chemical mechanisms and implications to different possible applications are discussed.

**CoPc on Different Surfaces**

The MPC–surface interaction is found to be strongly dependent on the surface type and its structure. For example, by precise thickness control of thin films, different quantum-well states can form in silicon-supported Pd islands. When MnPc is adsorbed on such Pd islands, oscillating Kondo temperatures as a function of film thickness will be found. CoPc adsorbed on Au, Ag, and Cu surfaces has been studied. The STM topographic images for CoPc on Au(111) and Ag(111) surfaces are similar, but a distortion is observed for CoPc on Cu(111). A $dI/dV$ spatial map gives the LDOS at a specific energy, thus providing more information with energy resolution than topographic images. We measure the $dI/dV$ map at energy points where a peak exists in the DOS curve. The $dI/dV$ patterns for CoPc on Au and Ag surfaces are similar, except for an about 0.6 eV energy shift of the peak positions, which should originate from the 0.6 eV work function difference between Au(111) and Ag(111) surfaces. However, the $dI/dV$ maps for CoPc on the Cu(111) surface are strikingly dif-
Different (Figure 2), indicating very distinct CoPc–Cu(111) surface interactions from those between CoPc and the Au or Ag surface.

The difference between Cu and Au or Ag surfaces can be understood by DFT calculations. According to the calculation results, the favorable adsorption site of CoPc on Au(111) and Ag(111) surfaces is the hcp site, while the bridge site becomes more favorable for the Cu(111) surface. A clear geometry deformation of the CoPc molecule is observed when it is adsorbed onto the Cu(111) surface. Projected density of states (PDOS) for CoPc on the Cu surface is also quite different from those for CoPc on Au and Ag surfaces (see Figure 2).

Different Metal Atoms in the MPC Molecule

An attractive feature of MPC is that the Pc ligand provides a similar chemical environment, and many different kinds of metal atoms can stably sit in the center of the molecule. Differences between the adsorptions of CoPc and CuPc on the Au(111) surface have been studied more than 10 years ago. From their STM topographic images, one can easily distinguish these two molecules: for CuPc, the central metal atom appears as a hole, but the Co atom in CoPc gives a protrusion in the STM image. This is because the Co(II) d^7 system has significant d-orbital character near the E_g, while the Cu(II) d^9 system does not. Further studies indicate that similar behavior can also be observed for FePc and NiPc.

Aiming to central metal atom based electronic structure engineering, we have systematically studied several 3d transition metal phthalocyanines on the Au(111) surface by DFT calculations. First, we consider the possible adsorption sites of MPC molecules on the Au surface. On the Au(111) surface, we have top, bridge, hcp-hollow, and fcc-hollow sites. The stable adsorption configuration is found to depend on the central metal atom type: MnPc prefers the top site, while other MPC (M = Fe, Co, Ni, or Cu) molecules prefer the hcp-hollow site. The distance between the metal atom M and the Au surface for MnPc and FePc are smaller than those for the other three molecules, which suggests that the interaction between these two molecules and the Au surface may be relatively stronger.

Except for NiPc, all other four MPC molecules have local magnetic moments (Table 1). After the molecules are adsorbed onto the Au(111) surface, different behaviors are observed: the magnetic moment on CoPc totally disappears, spin polarizations for MnPc and FePc are weakened, NiPc remains spin unpolarized, and the magnetic structure of CuPc is hardly affected by the substrate, too.

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TABLE 1. Theoretically Calculated Electronic Magnetic Moment ($\mu$) of MPC Molecules and Comparisons with STS Experimental Results

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<tr>
<th>MPC</th>
<th>magnetic moment</th>
<th>whether Kondo effect was observed in</th>
<th>adsorbed on</th>
<th>STS experiments for MPC on Au(111)</th>
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<td>MnPc</td>
<td>3.17</td>
<td>no, not observed on Pt island19</td>
<td>2.95</td>
<td></td>
</tr>
<tr>
<td>FePc</td>
<td>2.03</td>
<td>yes35,36</td>
<td>1.05</td>
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<tr>
<td>CoPc</td>
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<tr>
<td>NiPc</td>
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<td></td>
<td>0.00</td>
<td>not available</td>
</tr>
<tr>
<td>CuPc</td>
<td>0.54</td>
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Experimentally, the Kondo effect has been observed in the absorption systems with MnPc, FePc, and dehydrogenated CoPc (see Table 1).35,36 We do not expect to observe Kondo effect for NiPc or intact CoPc on the Au(111) surface, since there is no local magnetic moment. Although it has a local magnetic moment, so far there is no report on Kondo effect for CuPc. To explain this paradox, the angle-momentum resolved PDOS (Figure 3) is analyzed. For the adsorbed MnPc and FePc, the $d_{xz}$, $d_{yz}$, and $d_{xy}$ orbitals of the central metal atom dominate around $E_e$, and the $d_{z^2}$ orbital dominates for CoPc. However, for CuPc, the $d_{x^2}$ orbital dominates around $E_e$. Since the $d_{x^2-y^2}$ orbital is mainly distributed parallel to the surface, its interaction with the two electrodes should be much weaker than those of the other three MPC molecules. As a result, the Kondo temperature of adsorbed CuPc may be too low to be observed under current experimental conditions.

**Orbital Symmetry Match between STM Tip and Molecule**

So far, we have demonstrated the possibility of electronic structure engineering by changing the central metal atom of MPC and the surface. When we use STM as a research tool, we have many things to deal with the STM tip. Delicate STM tip modification has been widely used for various purposes.35,36 The most popular STM tip modification technique is based on molecular adsorption on the tip, which generally leads to a sharper tip. However, the adsorption of molecules onto the STM tip is very difficult to precisely control. Recently, we have developed a simple STM tip modification method to generate a “blunter” tip to achieve higher resolution in the energy scale.13

For CoPc on the Au(111) surface, a molecule−surface hybrid state, which is difficult to observe using a conventional STM tip, can be detected by a modified tip with coiled Fe layers on the conventional W tip. Both W and Fe/W tips give very similar single-molecule topographic images (Figure 4), which indicates that both tips provide a good spatial resolution. However, there is a remarkable difference between the STS curves in the negative bias region obtained by positioning

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**Figure 3.** (a−d) DOS projected on d orbitals with different symmetries in metal ions of different MPC molecules adsorbed on the Au(111) surface. Black curves represent the total DOS of metal ions, while blue, red, green, and cyan curves represent PDOS of $d_{xy}$, $d_{xz}$, $d_{yz}$, and $d_{x^2-y^2}$, respectively. (d) Schematic models of the s−type orbital of one molecule (such as the STM tip) and five d orbitals with different symmetries. Reproduced from ref 14.
FIGURE 4. (a) STM topographic image obtained at $-1.3$ V and 0.4 nA with a W tip. The red dots are the positions for STS measurements. (b) STM topographic image obtained at $-1.3$ V and 0.4 nA with the Fe/W tip. The blue dots are the positions for STS measurements. (c, d) $dI/dV$ curves measured above the CoPc molecule. Blue curves for the Fe/W tip, and the red curves are for the W tip. The positions where the tip was put are marked above the STS curves. The two $dI/dV$ curves at the bottom of panel c were measured for a clean Au surface. The $dI/dV$ curves are shifted vertically for a clearer presentation. Reproduced from ref 13.

FIGURE 5. (a) Iso-surfaces of the electronic charge density with an isovalue of $1.0 \times 10^{-4}$ e/Å$^3$ for the lowest unoccupied molecular orbital of the W tip. (b) Iso-surfaces of the electronic charge density with an isovalue of $1.0 \times 10^{-4}$ e/Å$^3$ for the highest occupied molecular orbital of the Fe/W tip. (c) Iso-surfaces of the electronic charge density with an isovalue of $1.0 \times 10^{-4}$ e/Å$^3$ for the orbital at $-0.42$ eV of CoPc/Au(111) adsorption system. Reproduced from ref 13.

Fe/W tip matches the surface orbital at about $-0.4$ V well, which contributes a large tunneling matrix element to enhance the $I_{2u}$ peak in $dI/dV$ spectrum.

FIGURE 6. (a) CoPc monolayer on a Au(111) surface ($7.5 \times 7.5$ nm$^2$). 1.2 V, 0.2 nA. The inset in (a) is a magnified molecule image (at $-0.7$ V and 0.2 nA) with a superimposed CoPc ball-stick sketch. (b) $I$–$V$ curves measured with the Ni tip (at $1.2$ V and 0.2 nA) over sites A, B, and C (marked in the inset of panel a) and with the W tip (at $-1.0$ V and 0.4 nA) over site A. The inset in panel b shows the results of five different Ni tips over site A taken at $1.2$ V and 0.5 nA. The curves in panel b and its inset are shifted vertically for clarity by separations of 0.3 nA. Reprinted with permission from ref 10, Copyright 2007, American Physical Society.

The previous result has demonstrated that there is plenty of room in STM tip preparation to probe richer chemistry and physics on the surface. In fact, STM can do more than surface characterization. For example, substrate–molecule–tip structure forms an excellent model system for molecular junctions, which is the fundamental unit used in nano- and molecular electronics.39,40

In nano- and molecular electronics, negative differential resistance (NDR) is an important phenomenon related to two-terminal logic devices.39 NDR has been realized based on the interaction between two localized narrow energy states41 or chemical change in the molecule involving reaction processes.42,43 In STM, observing NDR typically requires a sharp tip to produce the localized narrow energy state.50,54 Using the CoPc adsorbed on the Au(111) surface as an example, we have demonstrated that local orbital symmetry matching between tip and molecule may also play an important role in NDR.10

When we substitute the conventional W tip with a Ni tip, STS for CoPc on a Au(111) surface clearly shows a NDR effect with a maximum current at $-0.87$ V and a minimum current at $-1.34$ V (Figure 6). The NDR effect is sensitive to the offset from the C atom: a slight increase of the tip offset from the C atom (position B in Figure 6a) can smear out the NDR effect, and a normal monotonically behavior in the $I$–$V$ curve is recovered when the Ni tip is placed upon the benzene ring of CoPc (position C in Figure 6a). However, the NDR ratio ($I_{\text{max}}/I_{\text{min}}$) does not change with respect to the applied electric field or vertical tip–sample distance.
Single-Molecule Surgery

Single-molecule surgery can be used to tune the magnetic properties of the MPC adsorbed surface systems, which is very desirable in spintronics applications. By controlling the charge and spin state of a molecule using a gate voltage, researchers have found that the Kondo effect can be tuned reversibly. One can also change the chemical environment of a magnetic atom to control the Kondo temperature ($T_K$), as demonstrated by different CoCu$_2$ clusters on a Cu[111] surface. Single-molecule manipulation is required for on-site chemical environment change. STM can realize single-molecule manipulation by applying a strong bias voltage pulse, so it provides a powerful means to tune the Kondo effect.

For CoPc adsorbed on a Au[111] surface, as already mentioned previously, since the magnetic moment on Co in free CoPc is completely quenched by the molecule–substrate interaction, no Kondo effect is observed. The broad resonance centered around 150 meV below the $E_F$ is the Co d$_{z^2}$ orbital-mediated tunneling peak.

Interestingly, we found that the Kondo effect can be recovered by applying high-voltage pulses on the lobe edges of the CoPc molecule. In a typical current trace simultaneously measured during the application of a 3.6 V pulse on one of the four lobes of a CoPc molecule (Figure 7b), there appear two sudden drops of the current signal, indicating the sequential dissociation of the two H atoms from the benzene ring. The dehydrogenation process is also proven by the topographic images, which show that the bridge lobes in the four-lobe

**FIGURE 7.** (a) Typical dI/dV spectra measured at the center of a CoPc molecule at 5 K (black line), showing a d$_{z^2}$ orbital-mediated resonance, and a d-CoPc molecule at 5, 90, and 150 K (colored lines), showing strong resonance near the $E_F$. A spectrum from bare Au[111] (gray line) is shown for comparison. (b) Current versus time during two different voltage pulses on the brink of one lobe of CoPc. Black and red lines correspond to 3.3 and 3.6 V, respectively. The inset is a diagram of the dehydrogenation induced by the STM current. (c) The optimized computational model for the CoPc (upper panel) and d-CoPc (lower panel) adsorbed on Au[111]. (d) STM images of a single CoPc molecule during each step of the dehydrogenation process, from an intact CoPc on the left side to d-CoPc on the right side. (Image area: 25 x 25 Å$^2$). The color scale represents apparent heights, ranging from 0 Å (low) to 2.7 Å (high). Reprinted with permission from ref 9, Copyright 2005, American Association for the Advancement of Science (AAAS).

We note that neither the Ni nor the W electrode is of narrow band, and CoPc is very stable on the Au[111] surface under the present experiment conditions, which also excludes the possibility of chemical change on the adsorbed molecule. Therefore, there should be a new mechanism for the NDR effect observed in the CoPc/Au[111] system with the Ni STM tip. DFT calculations have been performed for the Ni tip and for CoPc adsorbed on the Au[111] surface. Since the observed NDR behavior occurs at negative sample bias voltage, we focus on the occupied sample states and unoccupied tip states. PDOS of the Co atom near the $E_F$ is dominated by its 3d orbitals, and there are three peaks corresponding to $d_{x^2-y^2}$, $d_{xy}$, and $d_{z^2}$ below the $E_F$. The energy of the second peak matches the energy point where NDR is observed. On the other hand, DOS for both Ni and W tips have broad bands around the $E_F$. However, d orbitals of different symmetries are evenly mixed for the W tip, but the $d_{xy}$ orbitals completely dominate in the DOS of the Ni tip near the $E_F$, with a sharp spectral profile at 0.23 eV and a full width at half-maximum (fwhm) of 0.4 eV. Such a fwhm fits quite well the energy region where the NDR was found in experiment.

With DOS of both sample and tip, the $I$–$V$ curve can be simulated with the modified Bardeen approach. According to spatial-symmetry mismatching, the electron tunneling probability between two orbitals with different magnetic quantum numbers is extremely small. We thus expect that the match between the $d_{xy}$ orbitals of the Co and Ni tip will cause the experimentally observed NDR, which is confirmed by direct $I$–$V$ spectrum simulation.
structure of the CoPC STM image disappear sequentially. Theoretical STM simulations for CoPC and dehydrogenated CoPC (d-CoPC) molecules agree well with experiment.

An increase of about 0.8 Å in apparent height of the molecular center (the Co ion) is observed after dehydrogenation. In contrast with intact CoPC, the d-CoPC molecule is difficult to move with the STM tip, indicating a stronger interaction between the d-CoPC molecule and substrate. This implication is confirmed by first-principles calculations, where the optimized geometry of d-CoPC adsorbed on a Au surface is no longer planar, with the end C atoms strongly bound to the gold substrate (Figure 7c). The upward shift of the central Co atom recovers the magnetic moment in the d-CoPC adsorption system, which leads to a significant Kondo peak near the $E_F$ in the $dI/dV$ spectrum of d-CoPC. The fitted Kondo temperature $T_K$ is about 208 K, much higher than the previously reported temperature for magnetic atoms or clusters on surfaces.45–49 In our control experiment with CuPC, no Kondo peak was found both before and after dehydrogenation.

A realistic surface may contain steps and defects. Effects of surface steps on the interaction between adsorbed molecule and surface has been studied.11 Most CoPC molecules adsorbed on monatomic steps of Au(111) have one or two of their lobes anchored on the higher terrace. We denote these two configurations as S1 and S2, respectively. Due to the featureless LDOS of Co ion at small positwe biases, the Co–Au distance can be roughly determined by the apparent height. Measured from the topographic images obtained at the same set point (with the same current and bias voltage). The apparent height of Co ions in S1 is higher than that in S2, as confirmed by DFT calculations (Figure 8). In $dI/dV$ spectra, the $d_{x^2}$ orbital-mediated tunneling peak is slightly shifted for CoPC adsorbed on step compared with that adsorbed on terrace.

Similar to those on terrace, S1- and S2-type CoPC can also be dehydrogenated via STM voltage pulse. Although the original molecules can be well-defined in two configurations, the treated molecules have various geometric structures. Applying a voltage pulse on one lower lobe (voltage pulse on upper lobes lead to sliding away of the molecule onto the lower terrace) may lead to a nonlocal change in the whole molecule. For example, a single voltage pulse on a lower lobe can cause the dehydrogenation of the opposite lobe. Interestingly, the Kondo effect can be observed for CoPC on step just after one or two lower lobes are treated.

The experimentally observed Kondo temperature $T_K$ strongly depends on the measured molecule–surface distance, and it can be well fitted by a simple empirical model based on the s–d exchange interaction between the localized spin and the surrounding conduction electrons.11 $T_K$ exponentially decreases with exchange interaction $J$ between the localized spin and conduction electrons, with $J$ depending on $d_{Co-Au}$. When $d_{Co-Au}$ is too small (smaller than 3.3 Å), the Co ion interacts strongly with the Au substrate. Therefore, considerable hybridization and charge transfer between Co 3d orbitals and Au make the magnetic moment completely quenched. In addition, in the presence of asymmetric crystal fields acting on the Co ion, a nondegenerated state may become energetically favorable compared with the degenerated spin 1/2 state, which also prohibits the Kondo spin-flip processes. For a large $d_{Co-Au}$ (larger than 3.7 Å), the exchange

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Interaction $J$ decays exponentially to zero, and $T_K$ will approach a limit beyond the ability of current STM. Only for intermediate $d_{\text{near}}$, the Kondo effect can be observed.

**Concluding Remarks**

Using the systems of MPC adsorbed on surfaces as examples, we have demonstrated that quantum control can be realized at the single-molecule scale by different means. By substituting the central metal atom M in MPC or by modifying the substrate surface, we can perform electronic structure engineering for the molecule absorbed on a surface, so as to switch on and off the Kondo effect. The STM manipulation technique can also be adopted to change the chemical environment of a metal atom. With a specially designed STM tip, we can probe a new molecule–surface hybrid state in a molecular junction presenting a non-dissipative effect. The combination of STM/STS and first-principles simulation has proven to be a powerful tool to study the geometrical and electronic structures of single molecules on surfaces.

We note that the ability to control the quantum world is very important for us. For example, it is critical in future electronics applications and new energy technology. Specifically, the ability to observe and control a single molecule on a surface may open many new possibilities. Single molecule manipulation is an important ingredient of the bottom-up approach of electronics. STM itself can be used to construct molecular junctions and to thus study transport properties in molecular electronics. The system of a molecule being adsorbed on a surface is also widely used as a model system for catalysis research. Bonding or charge transfer between molecule and surface are often very important for modulating the performance of catalysis.

Of course, it is never an easy target to fully control the quantum world. Although STM is indeed a powerful tool, what it measures corresponds to LDOS for an ideal STM tip instead of individual atoms. Therefore, interpretation of the STM observations is typically not straightforward, and time-consuming first-principles calculations are usually required. Tip preparation is also a big challenge. In most cases, a very sharp STM tip is a prerequisite. However, sometimes a carefully designed STM tip that is not necessarily very sharp in geometry but has specific frontier orbitals is also useful.

Many exciting works are expected in this field. Using a magnetic STM tip or applying an external magnetic field can provide more flexibility to control the quantum world. Combination of STM with other techniques, such as optical spectroscopy, is also an important direction.

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**BIOPHICAL INFORMATION**

Zhenyu Li received his Ph.D. in chemistry from University of Science and Technology of China (USTC) in 2004 under the supervision of Prof. Jinhong Yang. Since then, he has been working as a postdoctoral researcher in Prof. D. S. Koslov’s research group at University of Maryland, College Park, and in Prof. Shaul Mukamel’s group at University of California, Irvine. Currently, he is an associate professor at USTC. He is the recipient of the national excellent doctoral thesis award. His research interests include electronic structure theory and computation, electron transport in molecular electronics, and theoretical spectroscopy.

Bin Li received his Ph.D. in physics from USTC in 2002 under the supervision of Prof. Jian Guo Hou. He then worked as a postdoctoral researcher in Prof. C. T. Chan’s group at the Hong Kong University of Science and Technology and as a visiting scholar in Prof. W. T. Yang’s group at Duke University. From 2005, he has been an associate professor at USTC. His research interests include density functional theory, STM simulation, and QM/MM modeling.

Jinhong Yang, currently a Changjiang professor of chemistry, dean of the School of Chemistry and Material Sciences of USTC, received his Ph.D. in condensed matter physics from USTC in 1991. He is the recipient of the young chemist award from Chinese Chemical Society and the national award (grade two) for natural science and is the supervisor of two authors of the national excellent doctoral thesis award. His interests focus on developing first principles methods and their application on clusters, nanostructures, solid materials, surfaces, and interfaces.

Jian Guo Hou is a member of the Chinese Academy of Science, president of USTC. He received his Ph.D. in condensed matter physics from USTC in 1989. He is the recipient of the national award (grade two) for natural science, Ho Leung Ho Lee, Qiushi, and Tan Kan Lee, and the supervisor of an author of the national excellent doctoral thesis award. His main research interests focus on characterization and manipulation at the single-molecule scale on surfaces using scanning tunneling spectroscopy.

**FOOTNOTES**

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**REFERENCES**

Single-Molecule Chemistry of Metal Phthalocyanine Li et al.


Asymmetric Amplification in Phosphoric Acid Catalyzed Reactions
Nan Li, Xiao-Hua Chen, Shi-Ming Zhou, Shi-Wei Luo, Jin Song, Lei Ren, and Liu-Zhu Gong*

Methodologies involving chiral resolution, chiral auxiliary induced transformations, and asymmetric catalytic reactions, including those catalyzed by metal, biological, and organic catalysts, have been developed and, typically, these processes have exploited optically pure catalysts to ensure high enantioselectivity. In these reactions, the enantiomeric excess (ee) of the reaction product was linearly proportional to the ee value of the chiral catalyst or auxiliary. However, chemists have observed numerous exceptions to this linear relationship, some characterized by a positive nonlinear correlation between the ee value of the reaction product and that of the chiral catalyst or auxiliary. This phenomenon, termed asymmetric amplification, has not only provided cost effective asymmetric synthetic protocols in comparison with those using enantioselectively pure catalysts, but has also been considered a basis for the origin of homochirality in nature. In the last decades, metal-based asymmetric amplification catalysis has undergone great advances. Recent applications of asymmetric amplification in organocatalysis, particularly the use of biologically relevant molecules such as amino acids as catalysts, have advanced the long standing inquiry into the evolution of homochirality in the prebiotic system. However, the importance of asymmetric amplification in reactions catalyzed by phosphoric acids and its derivatives, an important class of pentavalent phosphorus compounds relevant to nucleic acids, has been less recognized.

During our studies on the phosphoric acid catalyzed Biginelli reaction, we found a strong positive nonlinear effect (NLE) for the reaction of para-nitrobenzaldehyde (2), thiourea (3), and ethyl acetoacetate (4) in the presence of 10 mol% of the non-enantiopure 3,3'-dithiophenylallyl bis-dervied phosphoric acid 1a in toluene (Figure 1a). In contrast, an absolutely linear effect was observed for the same reaction under almost identical reaction conditions except that chloroform was used as the reaction medium instead of toluene (Figure 1b). Kinetic studies revealed that the optically pure phosphoric acid afforded a much faster reaction in toluene (Figure 1c), but in chloroform, the optically pure and the racemic catalysts exhibited comparable catalytic activities (Figure 1d). Similarly, electron-rich benzaldehydes also participated in the reaction to show similar positive NLE as exemplified by 2-methylbenzaldehyde (see the Supporting Information).

The strong dependence of the NLE upon the solvent prompted us to investigate this observation in detail. In proton-catalyzed reactions, the nature of the solvent played a distinct role in the NLE, and this role was attributed to the solubility differences between racemic and optically pure samples. In the phosphoric acid catalyzed Biginelli reaction, we speculated that the significant dependence of the asymmetric amplification upon the solvent is also...
attributed to the enhancement of ee value of the solution arising from the differences in solubility of the racemic and optically pure phosphoric acids. When we compared the solubility of racemic and optically pure phosphoric acid 1 in toluene and in chloroform, we found that both the racemic and optically pure samples of phosphoric acid 1 were soluble and formed a clear solution. However, with stirring of the toluene solution a large amount of solid precipitated from the solution containing the racemic phosphoric acid (Figure 2).

Interestingly, the optically pure sample maintained a clear solution even with prolonged stirring (6h). In contrast, both racemic and optically pure samples were very soluble in chloroform and remained as clear solutions after being stirred for 36 hours.

![Figure 2]( observed changes to the toluene solutions of the pure enantiomer (left tube) and the racemic mixture (right tube) of the phosphoric acid with stirring at room temperature. The white object on the bottom is the stir bar.)

We next measured the ee values of the toluene solutions of phosphoric acid 1 having varying levels of enantiomeric excess (9.77%) at different concentrations (Table 1). The solid phosphoric acid 1 that precipitated from the solution has an ee value of less than 5%, and is somewhat independent of the optical purity of the original sample. Notably, the solution ee value was greatly enriched. A high solution ee value was obtained (89%) even when the enantiopurity of the phosphoric acid 1 was only 9% ee (entry 1). The solution ee value was slightly affected by the concentration of optically active phosphoric acid 1 solution because increasing the concentration from 0.01M to 0.02M led to an enhanced optical purity, in particular for the samples with low optical purity (entries 1–3). In contrast, the precipitates were also obtained with ee values of less than 5%, and were independent of the concentration.

Previous reports have revealed that a mixture of enantiomers occasionally exhibits unusual physical and chemical properties attributable to the formation of diastereomeric species in solutions. A racemic chiral compound had a 1H NMR spectrum that significantly differed from that obtained for the individual enantiomers. The solubility of the racemic compound, as opposed to that of its enantiomer, might result in the ability of the racemic phosphoric acid to form an aggregate which is a more energetically preferable diastereomeric species compared to that obtained from the optically pure enantiomer and is more difficult to dissociate in a nonpolar solvent. To investigate this possibility, we performed 1H NMR studies on the solution of phosphoric acid in [D₆]toluene. The 1H NMR spectrum gave a 1H NMR spectrum identical to that of the optically pure enantiomer, whereas the OH proton of the racemic phosphoric acid shifted downfield for about Δδ: 0.33 ppm with elapsing time. In sharp contrast, the optically pure sample maintained an almost identical 1H NMR spectrum (see the Supporting Information). This finding demonstrated that stronger intermolecular hydrogen-bonding interactions were present in the racemic system and enforced the association of racemic phosphoric acid molecules, thereby leading to the formation of heterochiral polymers that were less soluble than aggregates of the homochiral polymers.

We then undertook crystallography studies on the structures of racemic and enantiomERICALLY pure phosphoric acids (Figure 5). Powder X-ray diffraction (XRD) analysis showed that the solid from the powdered racemic 1 was the same as those of the corresponding single crystals (see the Supporting Information). Single crystals of the racemic and the optically pure forms of 1 were grown from toluene under an atmosphere of n-hexane vapors. Interestingly, the crystals had similar structural motifs, but different hydrogen-bonding patterns. In the heterochiral crystal, individual enantiomers of phosphoric acid 1 were aligned as a supramolecular chain stabilized by three hydrogen bonds formed between either the phosphoryl oxygen atom (P=O) or the hydroxy group with crystalline water (O1-W3, O2-W2, and O2-W3). The supramolecular chain is aligned parallel to the other chain consisting of the opposite enantiomer and features an addi-
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Figure 3. The crystal structures of racemic (a) and optically pure (b) 3,3’-diophenylphosphinic acid 1a. To simplify the structure, the 3,3’-diophenylphosphinic groups are omitted. The full structures are shown in the Supporting Information.

Figure 4. The ee values for a solution of and for the precipitated solid of 3,3’-diophenylphosphinic acid 1b (a) and 3,3’-di(2-naphthyl)phosphinic acid 1c (b).

tional six-membered hydrogen-bonded network (O2-W1 = 2.68 Å, O1-W2 = 2.51 Å), leading to a stable two-dimensional (2D) supramolecular sheet (Figure 3a). In the homochiral crystal (Figure 3b), the phosphonic acid also forms a supramolecular chain by forming two hydrogen bonds with crystalline water molecules. However, these two supramolecular chains are aligned antiparallel to each other and are connected by hydrogen bonds between O1 and O2, as well as between O2 and O. These are much weaker than those in the heterochiral crystal, as indicated by longer hydrogen-bond lengths (O1-O2 = 3.05 Å, O2-O3 = 2.97 Å), and lead to the formation of a somewhat distorted 2D supramolecular sheet. This finding is consistent with the conclusion drawn from the 1HNMR studies. The difference between the heterochiral and homochiral crystals suggests that the association of the racemate is more energetically favorable than that of the enantiomERICALLY pure phosphonic acid, and therefore contributing to the easier formation of the less soluble heterochiral phosphonic acid aggregates, thereby facilitating the precipitation of the racemate from the enantiomERICally enriched phosphonic acid solution (Figures 2 and 3). DFT calculations of the single-point energy for the dimer of both the racemic and enantiopure crystal structure of 1a indicated that the dimer of the racemate catalyst is more stable than the individual enantiomer by about 25.00 kcal mol⁻¹ (see the Supporting Information).

The preceding experimental evidence underpins the idea that, unlike the optically pure enantiomer, the racemic phosphonic acid forms energetically favored supramolecular aggregates that are less soluble in nonpolar solvents (e.g., toluene), and leads to the enhancement of solution ee values. The enhanced solution ee value resulted in the dramatic positive NLE observed in the phosphonic acid catalyzed Biginelli reaction. To investigate if this phenomenon is general for binol-derived phosphonic acids, we measured the solution ee value of 3,3’-diophenylphosphinic acid (1b) and 3,3’-di(2-naphthyl)phosphinic acid (1c), which are typical privileged catalysts for several enantioselective transformations. As shown in Figure 4, the enhancement in the solution ee value was observed in both cases, therefore asymmetric amplification should occur in the corresponding reactions catalyzed by these phosphonic acids when the precipitates, having low optical purity, are removed from the solution.

Finally, we investigated NLE in some reactions with or without removal of phosphonic acid precipitates having low ee values. In principal, if substrates and products do not contain hydrogen-bond-breaking elements and the reaction was performed in a solvent that shows different solubility for optically pure phosphonic acid and its racemic aggregates, a positive NLE should be observed even without removal of the precipitates. Indeed, we observed a positive NLE in the reaction of an imine with either an enamides or ethyl diazoacetate (Table 2, entries 1 and 2). However, a linear effect was obtained in the Friedel-Crafts reaction of indole (11) with nitrosoarene (12; Table 2, entry 3) and in an asymmetric transfer hydrogenation (Table 2, entry 5). This linear effect was probably a result of the presence of basic functional groups, such as amine and pyridine, which could break the aggregates of the insoluble racemic solid catalyst, thereby enabling them to dissolve in toluene and catalyze the reaction just as the enantiomERICally pure phosphonic acid. In contrast, when the phosphonic acid precipitates were removed, a strong positive NLE was observed in the Friedel-Crafts and transfer hydrogenation reactions, respectively (Table 2, entries 4 and 6).

In summary, we have found an unprecedented asymmetric amplification in reactions catalyzed by phosphonic acids.
Table 2: NLE in other reactions.\textsuperscript{26}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reaction</th>
<th>NLE (P)</th>
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<tbody>
<tr>
<td>1</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>\begin{align*} &amp; N \rightarrow H \ &amp; P \rightarrow H \end{align*}</td>
<td>+</td>
</tr>
</tbody>
</table>

\textsuperscript{[a]} All products have been reported previously\textsuperscript{26,29}. \textsuperscript{[b]} The “+” refers to positive NLE and “-” refers to linear effect. \textsuperscript{[c]} The precipitates of phosphoric acid were not removed. \textsuperscript{[d]} The precipitates of phosphoric acid were removed. Rz = benzoyl. M.S. = molecular sieves, PMP = para-methoxyphenyl.

positive nonlinear effect arose from the enhancement of the solution's values by formation of less soluble supramolecular structures of the racemic phosphoric acids through hydrogen bonds formed with crystalline water molecules. The NLE is a general phenomenon that was observed in different phosphoric acid catalyzed reactions with either removal of or in the presence of the racemic solid catalyst. Because pentavalent phosphorus compounds constitute key elements in living systems, particularly in nucleic acids, this finding may be related to the evolution of chirality in biomolecules in the prebiotic environment.

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\textsuperscript{[19]} Interestingly, the use of phosphoric acids as amplifiers of molecular chirality has been reported; see: R. Erkema, B. L. Perings, \textit{Org. Lett.} 2006, 8, 1331.  
\textsuperscript{[21]} The comparable results were observed in nondistilled toluene.  
Hybrid Composites

Biologically Inspired, Strong, Transparent, and Functional Layered Organic–Inorganic Hybrid Films**

Hong-Bin Yao, Hai-Yu Fang, Zhi-Hua Tan, Li-Heng Wu, and Shu-Hong Yu*
In the field of advanced materials design, good mechanical performance and multifunctionality are highly desirable and can often be realized through unique hybrid structures or composite materials. Strategies for materials design are highly multidisciplinary; just as the designed models in materials engineering are necessary to achieve excellent mechanical properties, the functional design of materials needs chemical or biological knowledge for the modification of materials. Surprisingly, in the process of evolution, nature has found a way to produce lightweight, strong, and high-performance materials with exceptional properties and functionalities by synergistically combining the models, methods, and approaches of materials engineering, chemistry, and biology. For example, seashell nacre and bones are well known for their hardness, strength, and toughness (superior to many synthetic ceramics and composites) 

continuously complemented by unique biological and biomedical properties. These natural materials consist of brittle biominerals connected by a small amount of protein and have highly sophisticated structures with complex hierarchical designs whose properties far exceed what could be expected from a simple mixture of their components. 

Continuing attention has been paid to the systematic study of natural materials with the objective of duplicating their properties in artificial materials. A number of different inorganic platelets including glass, graphite, silicon carbide, and clays have been used as fillers dispersed randomly into polymer matrices for the fabrication of artificial composite materials. The strength, hardness, and stiffness of these composites were enhanced compared to the pure polymer matrix or inorganic phase, but the improvement is still notably smaller than that realized by natural materials and that expected by theoretical models for reinforced polymers.

Recently, innovative techniques have been used to fabricate artificial composites by mimicking the micro- and nanostructures of natural materials. The mechanical performance of the obtained artificial materials is equal to or even better than that of natural materials. For example, layer-by-layer (LBL) deposition of polyelectrolyte and clay platelets was used to fabricate a nanostructured artificial nacre. Cross-linking of LBL-deposited poly(vinyl alcohol)/montmorillonite nanocomposites yielded materials with tensile strengths up to 450 MPa, which are stronger than the natural nacre. The microscopic layers formed by ice crystals were also used as a template for a fine ceramic structure, which could then be infiltrated with softer materials to build complex microstructured composites. The Al₂O₃/poly-(methyl methacrylate) composite with “brick-and-mortar” structure fabricated by this ice template crystallization method is 300 times tougher than its constituent. Furthermore, the spin-coating technique was used in the fabrication of lamellar alumina/chitosan hybrid films with high flaw tolerance and ductility.

Platelet-like inorganic building blocks are essential elements in the biomimetic fabrication of novel artificial composites, especially those aiming to recreate a biologically inspired layered “brick-and-mortar” micro- and nanostructure. However, in previous reports, the natural clay minerals and ceramic Al₂O₃ platelets used to make composites with biologically inspired structures just reinforced the polymer matrix without bringing other functionalities to these artificial composites. Herein, we use functional inorganic platelets to fabricate artificial organic-inorganic hybrid films with biologically inspired structures. In this way, the materials not only achieve high strength but are also simultaneously endowed with other special functionalities. The layered double hydroxides (LDHs), which can be represented by the general formula [M⁺ₙ⁻ⁿ⁺ⁿ⁺ⁿ⁺, (OH)ₙ]₀·(H₂O)ₓ where n is an integer, were chosen as the building blocks for fabricating biologically inspired, strong, and functional organic-inorganic hybrid films, as LDHs exhibit interesting optical, catalytic, magnetic, and fire-retardant properties. More importantly, these LDH platelets could be synthesized on a large scale by simple chemical precipitation. Although some studies have been conducted on the application of LDHs in composites, using LDH platelets as the inorganic bricks in the fabrication of biologically inspired organic-inorganic hybrid films has been rarely reported.

LDH micro- and nanoplatelets of Cu₃(OH)₂(NO₃)₂ (Cu-Cu), [Co₃₋ₓAlₓ(OH)₃]·[(CO₃)ₓ₋ₓ(OH)ₓ]·0.49H₂O (Co-Al-CO₃), and Eu(OH)₃·Ca₀·8H₂O (Eu-CI) were synthesized by slightly modified approaches according to previously published methods. The PXRD patterns of these LDH platelets are shown in Figure 1b, which indicates that as-synthesized micro- and nanoplatelets are pure phases. These platelets adopt layered structures with a series of 002 reflection peaks. Because of the intrinsically layered symmetry in the crystal structure, the LDH crystals prefer to grow into platelet-like morphologies, thus making them useful building blocks in the fabrication of layered organic-inorganic hybrid materials. The morphologies of the obtained Cu-Ni, Co-Al-CO₃, and Eu-CI crystals were characterized by scanning electron microscopy (SEM; Figure 1c–h). All of them display platelet-like micro- and nanomorphologies with a mean lateral size of 10–20, 3–4, and 1 μm and a thickness of 200, 100, and 10 nm, respectively.

In a first step, slightly hydrophobic amine-terminated silane species were attached to the surfaces of as-synthesized LDH platelets to achieve self-assembly of the colloidal...
inorganic building blocks into a highly oriented 2D structure (Figure 2a). Then, an ethanol suspension containing 1 vol.% modified LDH particles was added dropwise onto the surface of deionized water. After ultrasonication, a smooth and perfectly oriented monolayer of platelets was formed at the air-water interface (Figure 2b). The assembled platelets were easily transferred to a glass substrate with a layer of chitosan (applied by spin coating) by simple dip coating because of strong hydrogen bonding between the amine-terminated silanes attached to the surface of the LDH platelets and the amine groups in the matrix of chitosan on the glass substrate (Figure 2c,d). The substrate was dried at 50 °C in an oven in ambient atmosphere, and then a new layer of chitosan was spin-coated onto the dried substrate (Figure 2e). Sequential repetition of these steps leads to multilayered organic–inorganic hybrid films with a total thickness of a few tens of micrometers. Free-standing colored transparent hybrid films were obtained by peeling the films off the substrates with a razor blade (Figure 2f). The PXRD patterns of fabricated LDH–chitosan hybrid films (see the Supporting Information, Figure S1) indicate that the intrinsically layered symmetry of LDHs in the hybrid films is still kept, but with lower crystallinity, and other diffraction peaks that appeared are possibly due to the influence of amine-terminated silane species and chitosan molecules on the LDHs.

It has been demonstrated that Cu(NO3)2 and Co-Al-CO3 platelets could assemble at the air–water interface, forming highly oriented monolayer 2D structures, when amine-terminated silane species were attached to their surfaces (Figure 3a–c). Three types of Cu(NO3)2 and Co-Al-CO3 assemblies for fabricating LDH–chitosan hybrid films were designed: Type I: only Cu(NO3)2 or Co-Al-CO3 platelets were incorporated into the hybrid film (Figure 3a,c). Type II: Monolayers of Cu(NO3)2 and Co-Al-CO3 LDH platelets were alternately incorporated into the hybrid film (Figure 3b). Type III: The Cu(NO3)2 and Co-Al-CO3 LDH platelets were co-assembled at the air–water interface and then transferred to the substrate for the fabrication of the hybrid film (Figure 3b). The photographs in Figure 3 demonstrate that the hybrid films were all transparent and colored by the LDH platelets, and the color could be tuned by altering the combinations of LDH building blocks.

The cross-sectional microstructures of these hybrid films were investigated by SEM (Figure 4). For comparison, the pure chitosan film was fabricated by sequential LBL spin coating, but there is only one unit layer without lamellar microstructures inside this film (Figure 4a). By using LDH micro- and nanoplatelets as inorganic building blocks in LBL spin-coating procedures, the lamel-
lar microstructures were incorporated into these hybrid films (Figures 4b–d). Specifically, different 2D inorganic monolayers led to different micromorphologies of the hybrid films. This result indicates that the platelet-like LDH building blocks played a crucial role in the formation of lamellar microstructures that are similar to seashell nacre.

The tensile strength of fabricated films was measured to confirm the high strength of these hybrid films, which is thought to be brought about by the reinforcement effect of the inorganic LDH building blocks and by the biologically inspired layered microstructures. Figure 5a,b shows the tensile strength curves of pure chitosan film and of different LDH-chitosan hybrid films. The tensile strength of the hybrid films is much higher than that of the pure chitosan film, thus indicating that the LDH platelets reinforce the polymer matrix. It is worth mentioning that the tensile strength of the Cu(NO₃)₂-chitosan hybrid film reaches 150 MPa, thus making it stronger than some natural materials, such as nacre and dentin. and almost eight times as strong as pure chitosan film. A simple shear lag model based on the mechanics of composite structures was proposed to explain the enhancement of tensile strength of the hybrid films by addition of LDH platelets in hybrid films. In this model, the tensile strength of the hybrid film increases with an increase of the volume fraction (V_p) of LDH platelets (see the Supporting Information, Part II). In our designed fabrication procedure, the V_p of LDH platelets in the hybrid films could be tuned by controlling the concentration of the chitosan solution, and by using different co-assembly combinations of LDH platelets. Figure 5a shows that the tensile strength of Co-Al(NO₃)₂-chitosan hybrid films increases with a decreasing concentration of chitosan (a lower concentration of chitosan corresponds to a higher volume ratio of LDH platelets), which is consistent with the results of model analysis. Figure 5b shows that the tensile strength of hybrid films increases with the V_p of Cu(NO₃)₂ platelets, which are larger and thicker than Co-Al(NO₃)₂ platelets, thus further confirming the theoretical analysis that a higher volume fraction of platelets means higher tensile strength of the hybrid films. The Young’s modulus of the hybrid films is also enhanced by an increase of LDH V_p (see the Supporting Information, Table S1), which further confirms the strength reinforcement induced by the LDH platelets and biologically inspired layered structure. The wide range of mechanical properties of obtained films (tensile strength from 20 to 160 MPa, Young’s modulus from 2.3 to 12.7 GPa) is mainly due to the various compositions and fabrication types of obtained films.

The transparence for visible light of these fabricated films was investigated by light transmittance tests. Figure 5c shows 40–70% transparence across the visible spectrum for Co-Al(NO₃)₂-chitosan hybrid films, in comparison with 50–90% for a pure chitosan film. Figure 5d shows a very interesting result: the Cu(NO₃)₂ hybrid films only allow visible light (400–600 nm) to pass through, thus indicating their potential application in special window materials protecting objects from being hurt by UV light. The nice visible-light transparence of hybrid films is attributed to the flat and uniform orientation of the LDH platelets in the hybrid films. The light is not scattered...
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Figure 5. (a) Tensile strength curves of Co-Al2O3-chitosan hybrid films with different concentrations of chitosan comparison with pure chitosan film. (b) Tensile strength curves of hybrid films with different 2D inorganic-organic structures comparison with pure chitosan film. (c) Light transmittance spectra of Co-Al2O3-chitosan hybrid films comparison with pure chitosan film. (d) Light transmittance spectra of Co-NiO-chitosan hybrid films comparison with pure chitosan film.

by the sub-micrometer interfaces as in the original opaque powder form or many other composites with randomly dispersed LDHs.

A hybrid film with novel photoluminescent properties was also fabricated by using rare-earth metal EuCl nanoplatelets related to the LDHs as the functional building blocks (see the Supporting Information, Part III). It is interesting that the hybrid film not only emits red light but also emits blue light on irradiation with 360 nm light (see the Supporting Information, Figure S2a,b). The PL spectra analysis show that the blue light is caused by the chitosan matrix and that the red light comes from EuCl (see the Supporting Information, Figure S2c). Furthermore, the tensile strength of the hybrid film is also enhanced compared with that of the pure chitosan film with the inorganic platelet’s reinforcement (see the Supporting Information, Figure S2d).

In summary, a series of free-standing, strong, transparent, and functional layered organic-inorganic hybrid films reinforced with LDH micro- and nanoplatelets can be fabricated through LBL assembly procedure using series of LDH platelets as building blocks. The microstructures and tensile strengths of these hybrid films have been investigated to show biologically inspired layered microstructures with high performance in mechanical properties. The tensile strength of the Co-NiO-chitosan hybrid film achieved 160 MPa, which is eight times higher than that of a pure chitosan film and surpasses the strength of natural nacre. Furthermore, the EuCl rare-earth nanoplatelets can also be used as building blocks for fabrication of light-emitting and strong films, which can emit red light under irradiation of 360 nm UV light and maintain a fairly high strength.

Further extension of the present strategy should allow access to a variety of high-quality hybrid thin films with tunable mechanical properties and multifunctionality by use of inorganic micro- and nanoplatelets with tunable thicknesses, sizes, and functionalities as building blocks.

Experimental Section

Materials: Cupric nitrate (Cu(NO3)2·3H2O), aluminum chloride (AlCl3·6H2O), cobalt nitrate (Co(NO3)2·6H2O), urasa, europine oxide (Eu2O3), sodium chloride (NaCl), hexamethyldisilazane (HMDS), chitosan, glacial acetic acid (C2H4O2), and absolute anhydrous ethanol were purchased from Shanghai Chemical Reagent Co. Ltd. Silane coupling agent 1-aminopropyliethoxysilane (APTES) was purchased from YarHua Co. Ltd. All chemicals were analytical grade and used as received without further purification.

Synthesis of LDH platelet building blocks: Micro- and nanoplatelets of Co(OH)2·NiO [Co(OH)2·NiO] and Co(OH)2·NiO were synthesized according to the literature outlined in references [16a], [16b], and [18b], respectively. Details are given in the Supporting Information.

Preparation of chitosan film: Chitosan (2, 3, or 4 % w/v) was dissolved in deionized water (10 mL) containing 3 wt % acetic acid. After the mixture had been vigorously stirred for one day, it was expected that the amine groups of chitosan were fully protonated by the acetic acid.

Preparation of LDH platelets: In a typical procedure, APTES (5 mL), methanol (12.5 mL), and deionized water (37.5 mL) were mixed and stirred for 1 h to completely hydrolyze the silane species. LDH platelets synthesized as described above were added to the mixture, which was then stirred for 5 min. (Note: CuCl and the amine group of APTES can easily form a complex, so the mixture should not be stirred for longer than 5 min.) Finally, the silanized LDH platelets were filtered and washed several times with ethanol. The resulting LDH platelets were collected and dispersed in ethanol (30 mL).

Fabrication of organic-inorganic hybrid films: In a typical procedure, protonated chitosan (2, 3, or 4 wt %; 1 mL) was dropped onto a 2.5 cm x 2.5 cm glass substrate, and then a spin coater (MODEL WS-4000-SNPP-LITE SHOWN, Laurell Technologies Corporation) was used to spin the substrate at 1000 rpm for 1 min to form a flat layer of chitosan. The substrate with one layer of chitosan was dried at 50°C in an oven. The LDH platelets dispersed in ethanol were slowly dropped onto the water-air interface (a beaker was used to hold dispersed water) until one visible layer of thin film formed; then the beaker was evacuated mildly for 15 min. After evaporation, the LDH platelets form a compact inorganic layer. After finishing the two steps above, the glass substrate with chitosan was used to lift the inorganic thin film at the air-water interface through dip coating by hand. Then the film was dried at 50°C. The procedure was repeated 10 to 20 times to fabricate films comprising 10 to 20 layers of inorganic platelets. Note: the first and last layer should always be chitosan. The obtained films should be placed in the oven.
with high humidity, otherwise the film will become brittle and the color of hybrid film will change after several tens of days in the dry air.

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Keywords: chitosan · layered compounds · organic-inorganic hybrid composites · thin films


Direct Confined-Space Combustion Forming Monoclinic Vanadium Dioxides**

Changzheng Wu, Jun Dai, Xiaodong Zhang, Jinlong Yang, Fei Qi, Chen Gao, and Yi Xie*

Monoclinic vanadium dioxides VC2O4(M) are prototype materials for interpreting correlation effects in solids.1-4 Moreover, V2O5(M) undergoes a fully reversible metal–insulator phase transition between monoclinic V2O5(M) and rutile vanadium dioxide V2O5(R) (Supporting Information S1) with the benefits of huge temperature-induced changes in resistivity and selective optical switching, and has thus attracted great interest in the industrial and scientific communities for the construction of intelligent devices such as temperature sensors and energy-efficient smart windows.5-7 For more than 50 years after Morin's discovery,8-10 solid-state reactions were regarded as the exclusive synthetic route to V2O5(M).11-16 Obtaining V2O5(M) as the product of a solid-state reaction usually requires the rigid synergistic effects of high-temperature post-treatment, inert-gas atmosphere with precisely controlled flow, and long synthesis time, and this has made V2O5(M) one of the most expensive metal oxides up to now (Supporting Information S2).

Since the conventional synthesis temperature for functional oxides is usually higher than the phase transition temperature of about 68 °C, it is thought V2O5(M) can be formed solely by phase transition from the high-temperature V2O5(R) phase, and that controlling the formation of the V2O5(R) phase is the exclusive way of forming V2O5(M). V2O5(R) is well known as the thermodynamically most stable phase among the tens of kinds of vanadium dioxides.17,18 It consists of V2O5 octahedra that share two opposite parallel edges to form octahedral chains, which stack by sharing corners to form V2O5(R).19 The as-formed highly symmetric structure of V2O5(R), in which the vanadium atoms are at the centers of regular oxygen octahedra, is regarded to be a more stable structure. Other V2O5 polymorphs besides V2O5(R) usually have a shear structure20 in which deformed oxygen octahedra with vanadium atoms no longer at their center lead to metastable structures. Among these metastable structures, V2O5(B) is well known as the most common phase from solution reactions21,22. In this regard, we calculated the formation energy for V2O5(R) and V2O5(B) on the basis of density functional calculations (Supporting Information S3). Per [VO2] unit, V2O5(R) has a lower formation energy (5.611 eV) than V2O5(B). These calculations result further provide theoretical support for V2O5(R) as the thermodynamically stable phase.

Herein we report a new method to obtain V2O5(M), by direct combustion of an ethanolic solution of VO(acac)2 (acac = acetylacetonate) in a confined space (Figure 1). In our approach, the alcohol combustion in a confined space provides both sufficient thermal energy and a reducing/inert atmosphere, to overcome the reaction barrier and keep vanadium in the +4 valence state, respectively, and it leads to exclusive formation of thermodynamically stable V2O5(R). Since the phase transition between V2O5(M) and V2O5(R) is fully reversible, monoclinic V2O5(M) is formed from V2O5(R) when the product cools to room temperature. The whole process to form V2O5(M) only involves an appropriately sized beaker and an ethanolic solution containing VO(acac)2, offers high convenience, short reaction time, “green” chemistry, and no need for any complex manipulations or equipment.

The XRD pattern of the synthetic product (Figure 2a) matches well with that of standard JCPDS Card No. 43-1051 corresponding to monoclinic V2O5(M) with space group P21/c. The XRD pattern calculated from the V2O5(M) crystal cell (Figure 2a) is identical to the experimental pattern, and this provides direct evidence for the monoclinic phase of V2O5.

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monoclinic VO₂, and an atomic model (Figure 2c) with the same projected direction as in the HRTEM image, and this is further solid evidence for monoclinic VO₂.

The quality and composition of the VO₂(M) sample were further characterized by X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy. The XPS spectra show that the as-obtained sample consists of vanadium and oxygen, with the carbon peak at 284.6 eV as a reference. Also, the V₂p core-level spectrum (Supporting Information Figure S4-1b) shows that the observed value of the binding energy (516.4 eV) for V₂p₉/₁₆ is in good agreement with the literature values of bulk phase V=O. In addition, the binding energy difference (Δ) between the O1s and V₂p₉/₁₆ level was also used to determine the oxidation state of the vanadium oxide. The Δ value of the present VO₂(M) sample of 13.6 eV approaches that reported in the literature for V=O. The XPS spectra clearly reveal that in the as-obtained sample vanadium is in the +4 valence state, without any presence of the +5 valence state. Moreover, in the Raman spectrum (Supporting Information, Figure S4-2), the absence of the typical G band and D bands, which usually correspond to the E₂g mode of graphite and disordered graphite or glassy carbon, respectively, clearly verifies the absence of carbon-based species in our sample. Thus, both XP and Raman spectra confirm the high quality of the as-obtained VO₂(M) sample.

In the synthetic reaction, monoclinic VO₂ is obtained by ethanol-flame-induced pyrolysis of an initially formed VO₂(acac)₂ film. During solvent consumption by combustion, surface accumulation of soluble VO(acac)₂ results in a thin blue film of VO₂(acac)₂ on the glass inner wall by a process similar to colloidal particle formation by solvent drying. With increasing ethanol consumption by combustion, the air solution interface gradually drops, the ethanol flame can directly ignite the VO₂(acac)₂ film, and pyrolysis of VO₂(acac)₂ leads to formation of monoclinic VO₂ on the beaker wall substrate. In fact, the vanadium valence state and the flammable ligands play a vital role in the formation of VO₂(M) product (Supporting Information S5).

Moreover, ethanol combustion in a confined space provides both sufficient thermal energy and the reducing/inert reaction atmosphere to facilitate the formation of VO₂(M). In the formation mechanism of VO₂(M), ethanol combustion provides sufficient thermal energy to overcome the energy barrier for formation of the thermodynamically stable monoclinic phase of VO₂. Sufficiently high temperature is usually necessary for formation of the thermodynamically stable phase. In our case, the high-temperature reaction conditions come from ethanol combustion. Thermal infrared images were used to directly observe the spatial distribution of temperature during the reaction (Figure 3a). The high-temperature region lies at the center of the glass beaker, and the temperature gradually drops on moving away from the central position in the initial stage of the reaction. The high-temperature region extends downward as the air/liquid interface falls with proceeding ethanol consumption. At the end of the reaction stage, the high-temperature region even expands into the whole beaker and the red color corresponding to high temperature exhibits the shape of the beaker.

We measured the temperature distribution in the reaction space with a thermocouple detector as shown in Figure 3b. Due to the presence of sufficient oxygen, the temperature at the open end of the beaker is usually higher than that at
deeper points. The central point at the open end of the beaker has a temperature of 880-930°C, while those of two lower points were 700-750 and 600-648°C. The temperature on the inner beaker wall is lower than that of the central region due to significant thermal radiation of the glass wall. The inner wall at the open end still has the highest temperature of 370-400°C, while the lower lying regions of the inner wall have the lower values of 330-360 and 250-290 °C. The temperature data measured by thermocouple are in fair agreement with the temperature gradient in the thermal infrared images (Figure 3 a) along the radial and axial directions of the beaker, and this is further confirmation of the higher temperature in the confined space of the beaker. In other words, ethanol combustion in confined space provides sufficient thermal energy to ensure formation of thermodynamically stable monoclinic phase of VO₂.

Moreover, confined-space ethanol combustion also provides a reducing/inert atmosphere that prevents oxidation of monoclinic VO₂ to VO²⁺ oxides. To identify the intermediates and products of the ethanol flame, we performed experiments on premixed stoichiometric ethanol/oxygen flames and pyrolysis of ethanol with tunable synchrotron vacuum ultraviolet (VUV) photolization mass spectrometry (Figure 4 and Table S6 in the Supporting Information). The mass spectra clearly show that the dominant intermediate species in the ethanol flame, such as alcohol, aldehyde, H₂, and CO, are reductive and inert with respect to the valence state of vanadium (Supporting Information S6). Vanadium(IV) is usually sensitive to oxidation to VO²⁺ in air at high temperature (usually >300°C),[25] but the reducing/inert atmosphere in the confined space of the beaker prevents oxidation of the VO²⁺ oxide product to the VO³⁺ valence state. Kohnș–Hückhau

Figure 3. a) Temperature dependence of the resistivity of VO₂(M). b) ZFC magnetization as a function of temperature. Inset: differential curve of the ZFC curves in an applied magnetic field of 200 Oe. c) DSC thermal spectra of as-obtained VO₂(M) from the 1st to the 50th cycle. d) Cycling behavior of exothermic (red) and endothermic (blue) energy density for as-obtained VO₂(M).

Figure 4. Synchrotron-radiation photolization mass spectra measured on samples from the luminous zone of a premixed ethanol/oxygen flame. VUV photon energies (eV) are indicated in the figures.

about 5°C. Also, the ZFC magnetization curve (Figure 5 b) shows sharp increase in magnetic susceptibility around 67.8°C, which clearly indicates the structural phase change. The simultaneous decreases in magnetic susceptibility and electrical conductivity suggest formation of charge-density waves or a spin Peierls transition in VO₂(M).[22,23]

The first-order phase transition from rutile to monoclinic VO₂ usually involves a substantial entropy component. During the phase transition, under the driving force of decreasing temperature, a small distortion of infinite VO²⁺...VO²⁺ chains in rutile VO₂ occurs to form zigzag VO²⁺...VO²⁺ pairs that no longer linearly arrange in monoclinic VO₂(M). In this case, the small distortion of the atomic lattice and the change in conduction electrons are responsible for the entropy change due to discontinuity of the carrier density.[24] Therefore, thermal analysis studies reveal the direct character of the first-order structural transition in VO₂. Figure 5 c shows the DSC curves for as-obtained VO₂(M), which shows a narrow heating-cooling hysteresis of about 4.72°C and excellent cycling behavior for the structural phase transition. Fifty
heating and cooling cycles were all coincident, with no obvious deviation or distortion of the DSC curves. Also, the cycling behavior of exothermic and endothermic energy density (Figure 5d) further confirms the excellent exothermal and endothermal stability of the metal-insulator transition of as-obtained VO$_2$(M). In other words, the sharp increases in temperature-dependent resistivity and ZFC magnetization clearly mark the structural phase change, while the narrow heating-cooling hysteresis of the DSC curves and the excellent exothermal and endothermal stability suggests that our synthetic monoclinic VO$_2$ product is of high quality.

In summary, direct combustion of an ethanolic solution of VO(acac)$_2$, in a confined space affords monoclinic VO$_2$(M) and brings this expensive material into the realm of conventional laboratory synthesis. The whole process is remarkably convenient, with short reaction time, “green” chemistry, and no need for any complex equipment or manipulations. Real-time thermal infrared images and synchrotron-radiation photoionization mass spectra clearly reveal the dual role of ethanol in the reaction system. Moreover, since VO$_2$(M) is a prototype material for interpreting correlation effects in solids, the present synthesis of high-quality VO$_2$(M) provides a solid basis to settle the long-running debate$^{1,2}$ over the roles played by lattice distortion and electron-electron correlation in the temperature-driven metal-insulator transition, as well as for construction of intelligent devices such as temperature sensors and energy-efficient smart windows.

Experimental Section

VO$_2$(M): 2 mmol of VO(acac)$_2$ was loaded into a beaker (diameter: 50 mm, height: 70 mm) containing 40 mL of absolute ethanol. The VO(acac)$_2$ solution became transparent after strong stirring. The ethanolic solution was directly ignited and allowed to combus

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Enantioselective Oxidative Cross-Coupling Reaction of 3-Indolylmethyl C–H Bonds with 1,3-Dicarboxyls Using a Chiral Lewis Acid-Bonded Nucleophile to Control Stereochemistry**

Chang Guo, Jin Song, Shi-Wei Luo, and Liu-Zhu Gong*

* Dedicated to Professor You-Cheng Liu on the occasion of his 90th birthday

Cross-coupling reactions using C–H activation have emerged as robust alternatives to conventional transformations for the creation of new C–C bonds. The enantioselective variants hold great potential in synthetic applications, but continue to present formidable challenges. These reactions may be limited by the absence of binding sites in hydrocarbon compounds that enable the formation of a stereoselectively defined transition state for achieving high enantioselectivity. Furthermore, there are few examples of appropriate chiral ligands that tolerate the highly oxidizing conditions that are commonly used for C–H activation. In particular, the sp³ C–H-activation-based asymmetric C–C bond-forming reaction has largely relied on metal carbenoid insertion, although recent efforts have been directed toward enantioselective cross-coupling reactions involving sp³ C–H activation.

1,3-Dicarboxyl compounds of type 1 are able to coordinate to a variety of chiral Lewis acids to form chiral nucleophiles (1) that have been employed in various transformations with high levels of stereoselectivity. Inspired by these successes, we envisioned the control of the stereoselectivity in the C–H-activation-based oxidative coupling reactions (cross-dehydrogenative coupling) of dicarboxyls with arylmethyl compounds (2) by means of a similar chiral nucleophile to induce the stereoselectivity (Scheme 1).

2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) has been used in efficient oxidative coupling reactions involving sp³ C–H activation. Sodeoka and co-workers reported the asymmetric oxidative coupling reaction of N-Boc-protected tetrahydroisoquinoline with malonate by using a chiral palladium catalyst and DDQ as the oxidant, which provided the desired compound in 86% ee. Very recently, an organocatalytic asymmetric oxidative coupling of benzylic compounds with aldehydes was established with up to 86% ee. However, to the best of our knowledge, no highly enantioselective analogues of the oxidative coupling of 3-indolylmethyl C–H bonds with malonates are available. Indole derivatives have widespread applications in organic synthesis; therefore, the titled reaction holds great importance in organic synthesis. Herein, we report the highly enantioselective oxidative coupling of 3-indolylmethyl C–H bonds with malonates by sp³ C–H-activation using a chiral Lewis acid-bonded nucleophile to control stereochemistry.

We initially focused on the DDQ-oxidized coupling reaction of dimethyl malonate (1a) with 3-benzylindole (2a) in the presence of 10 mol % of Cu(OTf)₂ and 12 mol % of a chiral bis(oxazolines) ligand 4a. The reaction gave good enantioselectivity but a very low yield (Table 1, entry 1). The replacement of 4a with 4b provided a clean reaction to afford the desired product 3a in 80% yield, albeit with 31% ee (Table 1, entry 2). The stereoselectivity was further enhanced by using 5a as the ligand (64% ee; Table 1, entry 3). However, the substitution of metal triflates other than copper led to less-satisfactory reactions (Table 1, entries 4 and 5). Dibenzyl malonate showed comparably higher enantioselectivity than other counterparts (Table 1, entries 3, 6–7). However, 5b and 5c gave even lower levels of stereochemistry than 5a under...
Table 1: Seeking optimal chiral Lewis acids and optimization of reaction conditions

<table>
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<tr>
<th>Entry</th>
<th>R (1)</th>
<th>Metal</th>
<th>L&quot;</th>
<th>Solvent</th>
<th>% Yield</th>
<th>ee [%]</th>
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<tbody>
<tr>
<td>1</td>
<td>Me</td>
<td>Cu(DTQ)</td>
<td>4a</td>
<td>CHCl₃</td>
<td>18a</td>
<td>6</td>
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<tr>
<td>2</td>
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<td>Cu(DTQ)</td>
<td>4b</td>
<td>CHCl₃</td>
<td>5a</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Me</td>
<td>Cu(DTQ)</td>
<td>5a</td>
<td>CHCl₃</td>
<td>6a</td>
<td>84</td>
</tr>
<tr>
<td>4</td>
<td>Me</td>
<td>Mg(DTQ)</td>
<td>5a</td>
<td>CH₂Cl₂</td>
<td>17a</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>Me</td>
<td>Zn(DTQ)</td>
<td>5a</td>
<td>CH₂Cl₂</td>
<td>22a</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>Et</td>
<td>Cu(DTQ)</td>
<td>5a</td>
<td>CH₂Cl₂</td>
<td>15b</td>
<td>81</td>
</tr>
<tr>
<td>7</td>
<td>Bu</td>
<td>Cu(DTQ)</td>
<td>5a</td>
<td>CH₂Cl₂</td>
<td>16a</td>
<td>90</td>
</tr>
<tr>
<td>8</td>
<td>Bu</td>
<td>Cu(DTQ)</td>
<td>5b</td>
<td>CH₂Cl₂</td>
<td>5c</td>
<td>90</td>
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<tr>
<td>9</td>
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<tr>
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<td>5a</td>
<td>CH₃CN</td>
<td>21c</td>
<td>99</td>
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[a] The reaction of 1 (0.1 mmol) with 2a (0.1 mmol) was conducted at 25 °C. [b] Yield of isolated product. [c] Determined by HPLC. [d] At 0 °C. [e] Using CH₂Cl₂/F6HCH₂ = 1:15 as solvent.

Table 2: Investigating the scope of the procedure

<table>
<thead>
<tr>
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<th>Yield [%]</th>
<th>ee [%]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>H, 4-BrC₆H₄, Ph (3d)</td>
<td>97</td>
<td>93</td>
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<tr>
<td>2</td>
<td>H, 4-ClC₆H₄, Ph (3e)</td>
<td>82</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>H, 4-FC₆H₄, Ph (3f)</td>
<td>99</td>
<td>90</td>
</tr>
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<td>H, 4-FC₆H₄, Ph (3g)</td>
<td>74</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>H, 4-FC₆H₄, Ph (3h)</td>
<td>97</td>
<td>91</td>
</tr>
<tr>
<td>6</td>
<td>H, 4-NO₂C₆H₄, Ph (3i)</td>
<td>98</td>
<td>90</td>
</tr>
<tr>
<td>7</td>
<td>H, 4-CNCC₆H₄, Ph (3j)</td>
<td>81</td>
<td>90</td>
</tr>
<tr>
<td>8</td>
<td>H, 3-BrC₆H₄, Ph (3k)</td>
<td>72</td>
<td>93</td>
</tr>
<tr>
<td>9</td>
<td>H, 3-BrC₆H₄, Ph (3l)</td>
<td>96</td>
<td>94</td>
</tr>
<tr>
<td>10</td>
<td>H, 3-BrC₆H₄, Ph (3m)</td>
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<td>94</td>
</tr>
<tr>
<td>11</td>
<td>H, 5-MeOC₆H₄, Ph (3n)</td>
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<td>94</td>
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<tr>
<td>12</td>
<td>H, Ph, 4-FC₆H₄ (3o)</td>
<td>99</td>
<td>93</td>
</tr>
<tr>
<td>13</td>
<td>H, Ph, 4-ClC₆H₄ (3p)</td>
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<tr>
<td>14</td>
<td>H, Ph, 4-CNCC₆H₄ (3q)</td>
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<tr>
<td>16</td>
<td>H, Ph, 4-BrC₆H₄ (3s)</td>
<td>70</td>
<td>94</td>
</tr>
<tr>
<td>17</td>
<td>5-Cl, Ph, Ph (3t)</td>
<td>88</td>
<td>95</td>
</tr>
<tr>
<td>18</td>
<td>5-Cl, 4-BrC₆H₄, Ph (3u)</td>
<td>78</td>
<td>96</td>
</tr>
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</table>

[a] Unless indicated otherwise, the reaction was performed on a 0.1 mmol scale. [b] Yield of isolated product. [c] Determined by HPLC (see Supporting Information). [d] At -5 °C. [e] The reaction was performed on a 0.2 mmol scale. [f] At -5 °C.

A variety of structurally diverse 3-arylmethylindole derivatives were able to participate in the asymmetric oxidative cross-coupling reaction (Table 2). This procedure was effective and highly enantioselective for either electronically rich or poor 3-arylmethyl substituted substrates (up to 99 % yield and 94 % ee; Table 2, entries 1-11). The electronic properties of the aryl substituent imposed no apparent influences on the stereoselectivity (86-94 % ee), but had a great effect on the reaction conversion. Notably, variation of the 2-aryl substituent still provided a good reaction and excellent enantiomeric purity (Table 2, entries 12-16). The introduction of substituents onto the indole moiety was well-tolerated and resulted in excellent levels of enantioselectivity (95 % and 96 % ee, respectively; Table 2, entries 17 and 18). The configuration of 3t was assigned as R by X-ray analysis (see Supporting Information).

Besides malonates, 1,3-diketones were also tolerated under the reaction conditions. For example, acetylacetone (1d) and propionyl butanone (1e) both underwent oxidative coupling reactions with 2a in good yields and high enantioselectivity (70 % and 83 % ee, respectively; Eq. (1)). However, benzylic compounds, other than 3-indolylmethyl, failed to undergo the reaction. Despite this setback, the synthetic importance of indole derivatives gives this reaction great potential in asymmetric organic synthesis.

Oxindoles bearing a quaternary stereogenic center at the 3-position have great importance as building blocks in the synthesis of alkaloids. The products obtained from this asymmetric cross-dehydrogenative coupling can be readily transformed into oxindoles (Scheme 2). Removal of the benzylic group on 5c (94 % ee) by hydrogenation on Pd/C and followed by decarboxylation with copper(I) oxide produced 6 in 74 % yield. Methylated of 6 furnished 7 in 79 % yield. Following a known procedure, compound 7 was converted into oxindole 9 which contained an all-carbon quaternary stereogenic center, in 72 % overall yield whilst retaining the 94 % ee. The configuration of 9 was determined by X-ray analysis after it was transformed into N-benzylic derivative 10. Notably, Michael addition of 3-aryl oxindoles to cinnamates to giving highly enantioenriched oxindole 9 has not been reported.
2,3,4,4a,9a-Hexahydro-1H-pyrido[2,3-b]indoles have found widespread appearance in natural products. This skeleton can be enantioselectively accessed using the reaction reported here. For example, the N-methylation of 9 with iodomethane in the presence of sodium hydride, followed by an amidation with methylvamine readily produced 11. The reductive cyclization of 11 with lithium aluminum hydride furnished 12 in 75% yield (Scheme 3).

To identify the reaction intermediate, we performed ESR studies while monitoring the reaction. The solution of DDO in toluene exhibited a weak ESR signal whereas the addition of 3-benzyl indole, dibenzyl malonate, and the copper complex to the solution of DDO did not show any ESR signal (see the Supporting Information, Figures S1 and S2), thus indicating that a cationic radical species was generated to serve as the key intermediate of the coupling reaction. The presence of a Lewis acid actually enhances the oxidizing ability of the chiral copper complex and enhances the oxidizing ability by coordinating to the oxygen of DDO to facilitate the dehydrogenation of 3-arylmethyl indole (Scheme 4). Principally, the resultant cation exists as either a vinylogous iminium cation (Va) or a carbon cation (Vb). We then used DFT calculations to address the possible intermediate that participates in the reaction, which indicated that the positive charge delocalizes and distributes over the conjugate system, and thus the vinylogous iminium cation is more likely to be involved in the reaction.

Presumably, the vinylogous iminium cation would undergo deprotonation with IV to form a copper complex VI, which might be attacked by deoxynbenzyl compounds to give the final chiral product. However, the DFT calculation of bonding energies of VII with HOTf and of that with Cu(OTf)2 (Va versus VI) revealed that the vinylogous iminium cation VII is easier to form (Scheme 5), and thus Va rather than VI is a possible reaction intermediate.

On the basis of the experimental and theoretical studies, the reaction pathway to generate chiral products has been proposed (Scheme 6). After the copper-catalyzed dehydrogenation of 3-arylmethylindole to give Va, the resultant copper phenoxide (IV) serves as a base to deprotonate the dibenzyl malonate, generating a chiral anion intermediate VIII, which enantioselectively attacks the vinylogous iminium cation Va generated from the dehydrogenation to undergo a conjugate addition, giving the chiral product. Although chiral-copper-complex-catalyzed Michael addition reactions are well-established, the analogous procedure involving vinylogous iminium cations has not yet been reported.

The observed stereochemistry can be best explained by the proposed reaction models shown in Figure 1. Because of the steric repulsion between the Ar group and phenyl ring of the chiral catalyst, the transition state IXa is more favorably formed than IXb to preferentially give the desired product with observed stereoselectivity (Figure 1).

In conclusion, we have reported the highly enantioselective C-H-activation-based oxidative coupling reaction of 3-arylmethylindoles with dibenzyl malonate using chiral Lewis acid catalysts. Presumably, the reaction proceeded by...
a conjugate addition of the chiral Lewis acid bonded malonate ester to the vinylogous iminium cation, formed from dehydrogenation of 3-arylalkylindolines with DDQ. This reaction thus represents an unprecedented example in which a chiral Lewis acid successfully controlled the stereochemistry of a conjugate addition reaction of a nucleophile to the vinylogous iminium cations. In addition, the protocol also represents a unique sp² C–H-activation-based approach to access oxindole derivatives bearing quaternary stereogenic centers with high optical purity.

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Keywords: asymmetric catalysis · bis(exozoline) ligands · C–H activation · cross-coupling · Lewis acids


Communications


Ternary Heterostructured Nanoparticle Tubes: A Dual Catalyst and Its Synergistic Enhancement Effects for $\text{O}_2/\text{H}_2\text{O}_2$ Reduction

Chun-Hua Cui, Hui-Hui Li, Jin-Wen Yu, Min-Rui Gao, and Shu-Hong Yu *

The ability to control the chemical composition and the interface structure of multicomponent heterogeneous metallic catalysts without the support of porous carbon materials and foreign oxides is a challenging catalyst design area and can be aided by understanding the respective function of the metallic components. Generally, the alloy surface has an unusual electronic structure and arrangement of surface atoms in the near-surface region. A monolayer of noble metals, such as Pt or Pd, deposited on a host metal or alloy may induce strain and ligand effects, which can improve the activities. The promising strategies to change activities concern introducing a guest metal to form near-surface alloys and heterogeneous interfaces that endow the surface and interface with improved catalytic properties. However, the active metals, including Au, Fe, Ni, Cu, are usually alloyed or protected by noble metal layer, the naked-state effect of these active metals on the catalytic activity is unknown, but it is fascinating because of the unique interface and different oxidation state of the active metal.

Recently, some research work focused on the unique catalytic activity of dispersed metal nanoparticles supported on oxides and the metal/oxide interface boundary sites has provided evidence for the enhancement of the catalytic activity. However, these support oxides are usually impossible to reverse, which means that the oxides cannot be reduced into metallic state, and the oxidation state cannot be adjusted. Herein, we describe a Pd-Au/CuO@Cu heterostructured nanoparticle tube (HNT) catalyst, in which the CuO layer can be formed at lower potential when a metal (gold) component is added into the bimetallic PdCu system. The CuO layer formation is aided by the potential difference of the Au/Cu system. At negative potential, the CuO layer can be reduced and the PdAuCu catalyst is restored.

The PdAuCu HNT was synthesized by a facile, non-aqueous solution electrodeposition method. Unlike the seeded-growth method or metallic-precursor reduction for the synthesis of heterostructure nanoparticle materials, which require a mass of surfactants that will hinder the catalytic activity of metal surface, this strategy just uses dimethyl sulfoxide (DMSO) as a solvent and as a surfactant, which is bound to the metal surface by the sulfur atom in an inverted pyramid configuration and can be washed away easily owing to its weak absorption on the surface.

We synthesized a family of PdAuCu HNT catalysts by a one-step electrodeposition route onto an anodic aluminum oxide (AAO) template in anhydrous DMSO solution without the addition of any other surfactants (see Supporting Information). The aim of designing a tubular structure is to enhance the performance durability, eliminate the support-effect problem, and relax the Ostwald ripening and aggregation in contrast to the situation for particles. The scanning electron microscopy (SEM) images in Figures 1a and 1b show that the as-synthesized PdAuCu HNTs have lengths of several micrometers and a diameter of about 300 nm. The PdAuCu HNTs were completely dispersed and provided a three-dimensional space for the mass transfer of $\text{O}_2$ and $\text{H}_2\text{O}_2$ molecules. A typical transmission electron microscopy

![Figure 1](image_url)
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(TEM) image of the PdAuCu HNT shows the homogeneous wall thickness (Figure 1c). The tube wall is porous and consists of several layers of overlapped tiny particles, so the inner surfaces of the tubular catalyst are available as active sites (see Figure S1 in the Supporting Information). The size of the PdAuCu particles is about 2–6 nm, as revealed by the electron diffraction pattern (Inset in Figure 1e). The diffraction rings indicate small-size characteristics. For comparison, a PdCu nanoparticle tubular catalyst has also been prepared by the same route. The SEM and TEM images (see Figure S2 in the Supporting Information) indicate the PdCu has a tubular structure and the tube wall is thin enough for O2 and H2O2 molecules to penetrate through it. From the amplified TEM image, even the particle-like rough surface morphology was also observed. The PdCu nanoparticle had an average size of 3.5 nm as indicated by the HRTEM image (see Figure S2 in the Supporting Information).

The PdAuCu HNTs was characterized by means of powder X-ray diffraction (XRD). The results clearly showed that the PdCu catalyst has a partial alloying phase without the addition of Au, and the reflection appeared at 41.5° for PdCu (111). Weak Pd diffraction peaks were also detected (see Figure S3 in the Supporting Information). In the whole process, the atom percentage of Cu was kept approximately 55% and always constant. When about 3 at. % by atom % of Au was introduced into the PdCu catalyst, the Au(111) and Au(200) diffraction peaks appeared as did Pd(111), and the relative intensity of characteristic PdCu(200) decreased. With the increase of atom percentage of Au to 21%, the diffraction peaks of PdCu become weak, but the diffraction peaks of Au and Pd become clear. This phenomenon can be explained by a phase equilibrium of the Pd-Au-Cu ternary system. When the atom percentage of Cu was fixed at 55%, the introduction of Au changes the relative atom ratio of Pd, Au, and Cu, and moves the PdCu ratio outside that of the alloying phase isothermal section and the separated phase may form.

We further studied the surface composition of PdAuCu HNTs by X-ray photoelectron spectroscopy (XPS; Figure 1d). The strong signals from Pd3d and Au4d indicate the presence of Pd and Au. Because metallic Cu has low crystallinity and is absent in XRD patterns, the naked Cu/CuO was determined by energy position of the LMM Auger line of Cu (568 eV). Owing to the major reduction potential difference between Pd, Au, and Cu the preferential deposition may occur in this mixed Pd-Au-Cu ternary electrolyte solution. The energy-dispersive X-ray spectroscopy (EDX) maps were used to investigate elemental distributions and ratios of Pd, Au, and Cu metals (Figure 1e, inset, and Figure S4 in the Supporting Information). The image reveals that the elements Pd, Au, and Cu are uniformly dispersed in PdAuCu HNTs. The elemental distribution also represents the homogeneous particle distribution. So the dispersed particle provide plenty of interface area with highly active sites.

The electrocatalytic properties of PdAuCu HNTs toward the oxygen reduction reaction (ORR) along with those of PdCu and PdAu HNTs, and the commercial Pt/C catalysts (Johnson-Matthey, 20 wt %) have been investigated. Figure 2a shows the cyclic voltammogram (CV) curves. It shows that both the PdCu and PdAu have lower intensity redox waves than the PdAuCu catalyst. The redox waves of PdAuCu and PdAu appears at −0.12 and −0.21 V assigned to the reduction reaction of Cu2+ to Cu+ and Cu0 to Cu0.21 which indicates that the introduction of Au can lower the oxidation potential of Cu and favor the formation of active Cu0 species through the potential difference of AuCu system. Moreover, this CuO can be easily transformed to Cu under the negative CV reducing treatment. Undoubtedly, the presence of Cu0 species can improve the catalytic properties toward ORR, but whether this enhancement is due to Cu0+ mediators,10 or arises from adsorption sites to increase the concentration of O2 over the cathode12 is still controversial. In our experiment, the Cu0 species can form under lower potential in the presence of Au, demonstrating that both adsorption site and mediator function can occur (see Figure S5 in the Supporting Information).

The ORR measurements (Figure 2b) were performed in O2-saturated 0.1 M KOH solution at room temperature using a glassy carbon rotating disk electrode with a sweep rate of 50 mV s−1 at 1600 rpm. For the PdAuCu, PdCu, PdAu, and Pt/C catalysts, the low metal loading of Pd or Pt was 10.2 μg cm−2. The PdAuCu electrode showed an onset potential of 0 V, a shift of about 0.1 V to more positive potential than for the PdCu electrode, and the diffusion-limiting current from 0.8 to −0.25 V is very steady and nearly twice that of PdCu (the current density for PdAuCu at −0.2 V (vs. Ag/AgCl, if not specified otherwise) reaches 4.79 mA cm−2, nearly three times than that of PdCu (1.75 mA cm−2), indicating the accelerated O2RR kinetics caused by Au. The PdAu electrode for ORR has similar onset potential to PdAuCu, but the diffusion-limiting current is also lower, indicating that the
enhanced catalytic activity of PdAuCu cannot be achieved by just Au or Cu. Comparing this PdAuCu catalyst with the Pt/C catalyst, the half-wave potential for ORR shifts towards more positive potential by 42 mV. Moreover, PdAuCu has the highest mass activity and even 2.7 times higher than that of Pt/Cu and 1.6 times than that of Pt/C (Figure 2, inset). The improved activity of the PdAuCu catalyst for ORR might be due to the change of electronic structure and local reactivity of the surface in complex and mixed particle interfaces,[10] the presence of Cu²⁺ species formed at lower potential,[11,12] (see Figure S5 in the Supporting Information), and oxygen incorporation at the metal/oxide interface.[13]

The formation of hydrogen peroxide (H₂O₂) as an intermediate in ORR is the main energy loss on using gaseous O₂ as the oxidant, suggesting that H₂O₂ cannot be used directly as a liquid oxidant for fuel-cell applications because the H₂O₂ reduction occurs only with large overpotentials. We investigated the catalytic activity of PdAuCu towards H₂O₂ reduction (HR) in argon-saturated 0.1 M KOH aqueous solution (Figure 3a). The CV curves are very similar to those obtained for the ORR, which means H₂O₂ can also serve as an oxidant for fuel-cell applications and exhibit a high limiting current. For PdAuCu the trace is approximately a straight line from −0.8 to −0.25 V like for the ORR CV curves. At the present stage, the measured similar CV curves (with the oxygen-reduction current at the mixed kinetic-diffusion control region between −0.25 and −0.08 V) in the HR reaction, which are similar to the ORR reaction, are due to the catalytic decomposition of H₂O₂ and the high absorption of, and the reduction of, the in situ produced O₂. The high catalytic activity toward ORR of the PdAuCu catalyst as the mentioned above plus the unique decomposition of H₂O₂ and adsorption of O₂ induced the indirect reduction of the overpotential of the H₂O₂ reduction. The unique enhanced catalytic activities of PdAuCu may be due to the polarization effect at the noble metal and metal oxide interface.[20]

For fuel-cell applications, we also performed the investigation of the stability and durability of these catalysts in argon-saturated 0.1 M KOH aqueous solution (Figure 3a). The Pt/C catalyst has a drastic decrease even at the initial several circles. The Pt/C catalyst is also somewhat unstable but has a higher reduction current, conversely PdAu is very stable but has a lower current. The Pd/Cu catalyst shows synergistic effects from combining Pd/Cu and Pt/Cu catalysts, it is both stable and has a higher current. To evaluate the long-term electrocatalytic performance, the chronoamperograms (current–time profiles) of these catalysts were recorded with a bias at −0.2 V in argon-saturated 0.1 M KOH solution with 7.84 mM H₂O₂ (Figure 3b). It is clear that the Pt/C electrode in H₂O₂ solution undergoes accelerated corrosion and causes the degradation of Pt/C catalyst (I becomes less negative). As a result of the stability characteristics of Au towards ORR,[14] and as found in our case for the HR reaction, the long-term catalytic activity of the PdAuCu catalyst has been improved from 4 to 6 mA cm⁻² compared to Pt/Cu catalyst.

In conclusion, the as-synthesized PdAuCu HNT dual catalyst provides a promising route to the development of next-generation of mixed gas/liquid oxidant fuel cells with ultra-high electrical power output. The dual catalyst takes advantage of its unique catalytic properties for the HR reaction with an overpotential as low as for ORR. This PdAuCu HNT dual catalyst architecture also provides a new understanding of the synergistic effect, and consequently helps in designing new electrocatalysts with excellent stability and durability.

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![Figure 3.](image)
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Preparation of Photoluminescent Nanorings with Controllable Bioreducibility and Stimuli-Responsiveness**
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Nanoring materials with multiple functionalities have attracted significant attention owing to their potential applications in optical and electronic resonators, biological and chemical sensors, molecular imaging, and gene delivery.** Recently, several approaches have been proposed for fabricating nanoring materials, including synthesis of silver nanorings prepared from a one-pot procedure.[1] Au and Ag nanorings fabricated using the outer profile of silica nanoparticles as template,[5] and mesoscopic rings prepared by a method based on capillary force in the colloidal crystal.[6] Also, many interesting and unique properties of nanoring materials have been observed; for example, the toroidal structure of packed DNA is nature’s most efficient morphology for transporting genetic information, done particularly well by viruses. Some researchers want to mimic this process by condensing DNA into a nanoring morphology to improve the effect of gene therapy. The DNA nanoring packed in viruses is multifunctional, but the nanoring materials fabricated to date are limited by a lack of the multiple functionalities. Thus, the preparation of nanoring materials with multiple functionalities of stimuli-responsiveness, biocompatibility, biodegradability, and photoluminescence will be very attractive.[7] We report herein an easy approach to fabricating multifunctional nanorings by the assembly of DNA with a novel multifunctional hyperbranched macromolecule.

It has been reported that multivalent cations can condense DNA into nanorings under suitable conditions.[8,9] To prepare nanorings with multiple functionalities of stimuli-responsiveness, biodegradability, and photoluminescence, multivalent cations having these functionalities are prepared first and then used to condense plasmid DNA. Hyperbranched macromolecules are a special kind of macromolecule with three-dimensional structure. It is very easy to incorporate different functionalities into a single molecule of this type.[10] To develop photoluminescent nanorings with multiple functionalities, we prepared a novel disulfide-containing hyperbranched poly(amide amine) (HPAA) by Michael addition polymerization. Note that the syntheses of some linear disulfide-containing poly(amide amine)s have been reported, but these species easily condense plasmid DNA into nanoparticles; therefore, we prepared hyperbranched analogues.

The co-polyaddition reaction of 1-(2-aminoethyl)pyperazine (AEPZ) with N,N-cysteininesbacrylamide (CBA) and N,N-methylenecarbamoyl (MBA; Scheme 1) was employed in the preparation of the HPAA containing a 1:2 molar ratio of the CBA unit to the MBA unit (HPAA12). This synthetic route was chosen for three reasons: 1) The disulfide-containing HPAA with a 1.0 molar ratio of CBA to MBA (HPAA10) obtained by polyaddition of AEPZ and CBA (at a molar ratio of 1:2) and the disulfide-containing HPAA with a 1:1 molar ratio of CBA to MBA (HPAA11) obtained by polyaddition of AEPZ with CBA and MBA at a 1:2 molar ratio of AEPZ to MBA are not water-soluble, and they have low buffer capacity. 2) HPAA with a 0:1 molar ratio of CBA to MBA (HPAA01) obtained by polyaddition of AEPZ and MBA (molar ratio 1:2) degrades very slowly, and it is not stimuli-responsive. 3) Disulfide-containing HPAA12 obtained by co-polyaddition of AEPZ with CBA and MBA at
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A 1:2 molar ratio of AEPZ to CBA + MBA (molar ratio of CBA to MBA is 1:2) has good water-solubility, good stability in buffer, low cytotoxicity, fast biodegradability, good biocompatibility, and excellent buffer capacity. Most importantly, this kind of hyperbranched polymer can emit strong blue light owing to its special structure, as shown in Figure 1. The photoluminescence intensity increases with an increase of its molecular weight, and the photoluminescence becomes very weak after the polymer is reduced (see the Supporting Information).

Figure 1: The luminescence emission spectra of HPAA12, the inset image (A) is the optical micrograph of HPAA12 solution without filter, and (B) is its optical micrograph with filter.

Nanomaterials composed of assembled DNA remain an active topic for experimental and theoretical research because of their importance in cell biology, polymer physics, and biotechnology. The condensation is generally driven by an entropy increase associated with the release of counterions. The final condensate structures are determined by intermolecular forces including forces resisting condensation, such as entropy loss upon demixing of polymer and solvent and electrostatic repulsion among DNA chains, and favorable forces, such as correlated multivalent counterion fluctuation and cooperative hydration. The prepared HPAA12 (Mw is 38 kDa) has many primary, secondary, and tertiary amines, which can bind and assemble DNA into nanorings. An assay excluding ethidium bromide shows that HPAA12 can bind strongly to DNA. Vortexing DNA solution in sodium acetate buffer with HPAA12 produces polyplex particles approximately 150 nm in diameter, as determined by dynamic light scattering (DLS) experiments. The zeta potential value of the formed polyplex nanoparticles is approximately 40 mV (see the Supporting Information).

To characterize the structure of the formed polyplex in detail, we transferred the nanoparticles onto mica. AFM images show that the polyplex particles have nanoring structure and are approximately 100 nm in diameter (Scheme 2 and Figure 2A1). Furthermore, hyperbranched disulfide-containing poly(amide amine) (Mw of 15' and 58 kDa) also easily condense DNA into toroidal nanoparticles. However, linear disulfide-containing poly(amide amine) were found to condense DNA into spherical nanoparticles approximately 150 nm in diameter when DNA solution was vortexed in sodium acetate buffer at an amine to DNA phosphate (N/P) ratio of 4.1 (as shown in Scheme 3). Therefore, the topology of disulfide-containing poly(amide amine)
determines the structure of the formed polypelex: hyperbranched poly(amide amine) effectively condense plasmid DNA into nanoring-structured polypelexes, while linear poly(amide amine) easily condense DNA into spherical nanoparticles. The possible reason is that plasmid DNA is highly charged, which makes it rigid owing to the electrostatic repulsion among DNA chains, and so it is in a stretched structure; it becomes weakly charged and flexible after condensing with linear poly(amide amine), because the electrostatic repulsion among DNA chains becomes weak. Hence the DNA strand comes into a global structure and subsequently forms nanoparticles after further complexing with linear poly(amide amine). However, DNA is still highly charged after complexing with disulfide-containing HPAAAs; some parts are highly positive, and some parts are highly negative; furthermore, the positive parts complex with the negative parts, which yields DNA strand (see the Supporting Information). Therefore, the disulfide-containing HPAAAs easily condense DNA into toroidal structures, while some disulfide-containing linear poly(amide amine) easily condense DNA into nanoparticles.

We have not obtained AFM images of the intermediates during the formation of the polypelex, but we used AFM to trace their disassembly in the presence of dithiobiotit. It is clear that the size of some nanorings increases while the size of the ring wall decreases, as some hyperbranched macromolecules are reduced in the presence of dithiobiotit and some folded strands unfold. During the disassembly of spherical nanoparticles, some random coil structures were observed (see the Supporting Information), which further verifies the presumed condensation mechanism. The N/P ratio and the molecular weight of disulfide-containing hyperbranched poly(amide amine) have some effects on the formation of nanoring structure: toroidal structures were observed at N/P ratio of approximately 5, but the spherical nanoparticles formed when the N/P ratio was over 10; toroidal structures were observed when the MW of HPAA is above 15 kDa, but spherical nanoparticles formed when the MW of HPAA was about 2 kDa. Of course, factors such as the pH of the buffer, the chemical structures of the poly(amide amine) chain, and incubation time also affect the morphology of the polypelex. On the other hand, it is very interesting that these nanorings can emit strong blue and green light and weak red light when 330–385, 460–490, and 510–530 nm excitation filters were used, respectively. The nanorings were transferred onto a microscope slide, and the strong blue light was observed from the optical microscope after removing solvent (as shown in Figure 2B1). The disulfide-containing poly(amide amine) is of very low cytotoxicity (see the Supporting Information), therefore the formed nanorings are photoluminescent with good biocompatibility.

The formed nanorings contain disulfide linkages in the ring wall. These disulfide linkages can be controllably bioreduced, and the nanorings will degrade if the disulfide linkages in the ring wall break. These nanorings are sensitive to dithiothreitol (DTT) and glutathione (GSH). After the nanorings were treated with 2 μM and 20 mM DTT, respectively, the solution was transferred onto microscope slides at different time intervals. There is almost no change in photoluminescence for the nanorings treated with 2 μM DTT even after 120 min; however, there is almost no photoluminescence for the nanorings treated with 20 mM DTT for 60 min, and the fluorescent optical micrographs show that the photoluminescence intensity decreased with time after treatment (Figure 2B1–4), thus showing that these nanorings are stimulus-responsive. This stimulus-responsive photoluminescence may be used in molecular imaging.

The nanorings were also imaged in buffer solutions after DTT solution was injected. The DTT concentration was maintained at 20 mM in the cell, which is a similar level as the in vivo GSH concentration in the nucleus. AFM imaging ensued immediately after the introduction of DTT. The results show that the nanorings disassembled slowly and completely disassembled in approximately 60 min (Figure 2A2–4). However, the ring structure remained unchanged after the nanorings were treated with 2 μM DTT for 120 min, which indicates that the disassembly of the formed nanoring is controllable. This controllable disassembly is very useful in gene and drug delivery, as the release of gene or drug can be controlled in cell. In the gene delivery experiment, it is found that the gene transfection efficiency using these stimuli-responsive delivery vectors is higher than that using non-stimulus-responsive delivery vector (see the Supporting Information).

In summary, a novel multifunctional disulfide-containing hyperbranched poly(amide amine) with stimuli-responsive biocompatibility, biodegradability, and photoluminescence was developed, and this polymer can effectively assemble plasmid DNA into photoluminescent nanorings with disulfide linkages in the ring wall. These fabricated nanorings are not only photoluminescent but are also stimuli-responsive and biocompatible and can be controllably bioreduced, which will have potential applications in gene and drug delivery and molecular imaging.

**Experimental Section**

Synthesis of hyperbranched poly(amide amine) HPAA12: The synthesis of disulfide-containing bioreducible hyperbranched poly(amide amine) chain, and incubation time also affect the morphology of the polypelex. On the other hand, it is very interesting that these nanorings can emit strong blue and green light and weak red light when 330–385, 460–490, and 510–530 nm excitation filters were used, respectively. The nanorings were transferred onto a microscope slide, and the strong blue light was observed from the optical microscope after removing solvent (as shown in Figure 2B1). The disulfide-containing poly(amide amine) is of very low cytotoxicity (see the Supporting Information), therefore the formed nanorings are photoluminescent with good biocompatibility.

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In summary, a novel multifunctional disulfide-containing hyperbranched poly(amide amine) with stimuli-responsive biocompatibility, biodegradability, and photoluminescence was developed, and this polymer can effectively assemble plasmid DNA into photoluminescent nanorings with disulfide linkages in the ring wall. These fabricated nanorings are not only photoluminescent but are also stimuli-responsive and biocompatible and can be controllably bioreduced, which will have potential applications in gene and drug delivery and molecular imaging.
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mido amine) by Michael addition copolymerization is similar to earlier reports.[5] In a typical experiment, AEPZ (1.250 mg, 1.0 mmol), CBA (1.736 mg, 0.67 mmol), and MBA (2.05 mg, 1.33 mmol), the molar ratio of AEPZ to CBA to MBA is 1:2:2, were added into a vial and dissolved in methanol/water (6.0 mL, 3:2 v/v). The reaction was allowed to proceed at 50°C for 90 h, yielding hyperbranched polymer with vinyl end groups. Then AEPZ (1.20 mg) was added to terminate the vinyl units. The resulting hyperbranched HPAAD12 was obtained by precipitation in cold acetone and drying under vacuum for 2 h at room temperature. A 2% solution of the prepared polymer was used in photoluminescence experiments; the quantum yield is 0.21.

Preparation of nanorings by assembly of DNA with hyperbranched poly(amide amine): DNA (30 mg mL−1) in 30 mM sodium acetate buffer (pH 5.1) was used to prepare nanoring-structured materials at an amine to DNA phosphate (NP) molar ratio of 4:1. Then HPAAD12 (2.0 mg mL−1) solution was added to the DNA solution and mixed by vortexing at 3000 rpm for 60 s, and the solution was incubated at room temperature for 20 min. A 30 μL sample of nanoring particles was transferred onto approximately 1 cm2 of freshly cleaved mica, and the surface was rinsed with deionized water.

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Reversible Three-State Switching of Multicolor Fluorescence Emission by Multiple Stimuli Modulated FRET Processes within Thermoresponsive Polymeric Micelles

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Energy transfer between light-absorbing donors and energy-receiving acceptors occurs on the nanometer distance scale. One of the key issues in designing effective multichromophore luminescent systems is the precise spatial arrangement of the fluorophores. By learning from existing systems, researchers have exploited a variety of artificial nanostructures such as dendrimers, nanoparticles, (multi-layered) thin films, and supramolecular assemblies to achieve nanoscale control and accurate location of chromophores, leading to the modulation of luminescence efficiency through the enhancement or restriction of fluorescence resonance energy transfer (FRET) processes. In view of the microenvironment complexity in certain bio-applications such as imaging, biosensing, and clinical diagnosis, it is highly desirable to combine the concept of external stimuli-triggered activation/deactivation of specific emitting fluorophores to achieve higher temporal and spatial detection resolution. Although there are a few examples of luminescent polymeric assemblies and nanoparticles exhibiting two-state switching of luminescence, systems exhibiting both reversible three-state on/off switching of the fluorescence emission and stimulus-responsive tuning of the spatial distributions of FRET donors and acceptors (FRET efficiency) has, to our knowledge, not been accomplished.

Herein we report the fabrication of amphiphilic and thermoresponsive diblock-copolymer based luminescent micelles exhibiting three-state switchable multicolor fluorescence emission by external stimuli-modulated FRET processes (Scheme 1). The FRET system consists of one type of donor dye and two types of acceptor dyes, and fluorescence emission of the latter two can be switched on and off by changes in pH and light irradiation (UV/Vis), respectively. Such multicolor luminescent polymeric assemblies can act as sensitive ratiometric probes for pH and temperature. Most importantly, the detection sensitivity can be further improved at elevated temperatures because of the closer proximity between FRET donors and acceptors resulting from the thermoresponsive collapse of micelle coronas.

Three polymerizable fluorescent dyes, NBDAE, pH-switchable rhodamine B based monomer (RhBAM: synthesis: Scheme S1, NMR data: Figure S1 in the Supporting Information), and photoswitchable SPMa, were synthesized. Amphiphilic diblock copolymer, P(ST-co-NBDAE-co-SPMa)_{98}b-(P[NIPAM-co-RhBAM])_{12}o, bearing NBDAE and SPMa moieties in the hydrophobic polystyrene (PS) block and RhBAM moieties in the thermoresponsive poly(N-isopropylacrylamide) (PNIPAM) block was synthesized by sequential reversible addition-fragmentation transfer (RAFT) polymerization (Scheme S2, Figures S2 and S3 in the Supporting Information). For comparison, a series of PS-b-PNIPAM diblock copolymers with varying combinations of NBDAE, SPMa, and RhBAM residues were also synthesized. The molecular parameters of all diblock copolymers used in this work are summarized in Table S1 in the Supporting Information.

In aqueous solution, P(ST-co-NBDAE-co-SPMa)_{98}b-(P[NIPAM-co-RhBAM])_{12}o self-assembles into spherical micelles, as evidenced from AFM results (Figure S4 in the Supporting Information), which consist of PS cores embedded with NBDAE and SPMa dyes and thermoresponsive PNIPAM coronas embedded with RhBAM dyes. Surface tensiometry measurements at 25 ºC revealed a critical micelle concentration (CMC) of 2.3 x 10^{-3} g L^{-1} (Figure S5 in the Supporting Information). The micellar solution at a concentration of 1.0 g L^{-1} exhibits thermo-induced aggregation above 28 ºC owing to the well-known lower critical solution temperature (LCST) phase-transition behavior of PNIPAM coronas (Figure S6 in the Supporting Information). Dynamic laser light scattering (DLS) analysis further revealed intensity-average hydrodynamic diameters (Dh) of 50 nm and 36 nm for the micellar solution at 25 ºC and 35 ºC, respectively (Figure S7 in the Supporting Information). A comparison of AFM and dynamic LLS analysis results indicated the shrinkage of the thickness of the micellar coronas from approximately 18 to 11 nm upon heating above the LCST of PNIPAM coronas.

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Scheme 1. Construction of a polymeric-micelle-based reversible three-state switchable multicolor luminescent system from amphiphilic and thermoresponsive diblock copolymer P(St-co-NBDAE-co-SPMA)-b-P(NIPAM-co-RhBAM). See text for details.

Among the three copolymerized dyes, NBDAE exhibits strong green fluorescence emission at 520 nm, the intensity of which is almost irrespective of solution pH in the range pH 3–9 (Figure S8 in the Supporting Information).20 The pH-sensitive RhBAM moiety exists in the spirolactam form above pH 6 and exhibits no fluorescence emission, whereas below pH 6 it transforms into the "open" form and emits strong fluorescence at 580 nm (Scheme 1).21,22 Thus, the fluorescence emission of RhBAM residues can be facilely switched on and off by pH variations (Figure S9 in the Supporting Information). The photoswitchable fluorescence emission behavior of SPMA has been well-documented.23–25 SPMA exists in the colorless spiropryan form under visible light; upon UV irradiation, it transforms from the nonfluorescent form into the merocyanine form (MCMA), which has fluorescence emission at 645 nm (Scheme 1). Considering that the fluorescence emission of both NBDAE and MCMA can be enhanced when located in hydrophobic microenvironment,26,27 we choose to copolymerize NBDAE and SPMA moieties into the hydrophobic PS block and pH-sensitive RhBAM dyes into the thermoresponsive P(NIPAM) block.

Interestingly, the NBDAE fluorescence emission band overlaps well with the absorbance bands of ring-opened RhBAM and MCMA moieties (Figures S8 and S10 in the Supporting Information). Thus, they can be integrated into the diblock copolymer to construct efficient luminescent systems with FRET features.28–30 P(St-co-NBDAE-co-SPMA)-b-P(NIPAM-co-RhBAM)nm possesses one type of donor dye (NBDAE) and two types of potential FRET acceptor dyes, RhBAM and SPMA. The fluorescence emission of the latter two can be switched on and off by pH and light irradiation (UV/Vis), respectively. This novel type of dye combination might lead to the construction of three-state switchable multicolor luminescent systems [NBDAE emission at pH 7 under visible light, NBDAE/RhBAM (open form) FRET system below pH 6 under visible light, and NBDAE/MCMA FRET system at pH 7 upon UV irradiation]. Moreover, the efficiency of the FRET process between NBDAE and ring-opened RhBAM below pH 6 can be facilely tuned by temperature variations by exploiting the thermally induced collapse of P(NIPAM) coronas, which results in the closer proximity between FRET donors and acceptors (Scheme 1).

We then explored the pH-modulated luminescence behavior of P(St-co-NBDAE-co-SPMA)-b-P(NIPAM-co-RhBAM)m, micellar solution; under the initial conditions, SPMA moieties in the PS block are colorless and nonfluorescent. Above pH 6, only the green fluorescence emission of NBDAE dyes (λmax = 518 nm, Figure 1A) is observed, as RhBAM residues exhibit no emission, that is, a FRET process between NBDAE and RhBAM or SPMA does not occur. Upon adjusting to pH < 6, RhBAM moieties convert into the fluorescent ring-opened form, as evidenced from the appearance of a new fluorescence emission band at around 580 nm (Figure 1). Figure 1C clearly shows that the pH decrease in the range pH 3–6 results in an increase of emission intensity (580 nm) of ring-opened RhBAM, accompanied by a considerable decrease of NBDAE emission intensity at 518 nm. The pH-induced fluorescence emission changes can also be visualized by the naked eye, as evidenced from the transition from green emission at pH 7 to yellow emission at pH 3 (Figure 1B). The above results indicated the occurrence of a FRET process between NBDAE within micellar cores and ring-opened RhBAM moieties within micellar coronas below pH 6, as the emission of NBDAE residues in diblock copolymer micelles is essentially independent of solution pH (Figure S8 in the Supporting Information). When the solution pH was cycled between pH 7 and 3, we observed repeated changes of emission intensity at
obtained for dual dye-labeled diblock copolymers, P(Si-co-NBDAE$_{12}$)-b-P(NIPAM-co-RhBAM)$_{30}$ and P(Si-co-NBDAE-co-SPA)$_{50}$-b-P(NIPAM$-$co-RhBAM)$_{30}$ as control samples (Figures S12–S14 in the Supporting Information). The above results indicated that the micellar solution of P(Si-co-NBDAE-co-SPA)$_{50}$-b-P(NIPAM$-$co-RhBAM)$_{30}$ can act as sensitive ratiometric pH probes in the range pH 3–6 (Figure 1C and Figure S15 in the Supporting Information). We further employed the thermo-induced collapse of PNIPAM coronas to adjust spatial proximity between NBDAE and ring-opened RhBAM moieties located within micellar cores and coronas, respectively (Scheme 1). As shown in Figure 1A,B, heating the micellar solution from 25°C to 35°C leads to a yellow-to-orange transition of the fluorescence emission. We can clearly observe the considerable increase of RhBAM emission and the dramatic decrease of NBDAE emission at pH 3 and 35°C, relative to that at pH 3 and 25°C. This result indicated the occurrence of a more-efficient FRET process for diblock copolymer micelles with collapsed PNIPAM coronas. A more-detailed investigation revealed that emission intensity ratios $I_{RhBAM}/I_{NBDAE}$ exhibit around a 3.5 times increase in the narrow temperature range 23–32°C (Figure 2a and Figure S16 in the Supporting Information). Thus, the diblock copolymer micelles can also act as ratiometric fluorescent thermometers. From Figure S15 and

580 nm, indicating that pH-induced emission switching is fully reversible (Figure S11 in the Supporting Information).

Under visible-light conditions, the presence of SPA moieties in the diblock copolymer does not exhibit any appreciable effects on the pH-switchable luminescence behavior, as evidenced from spectrofluorimetric results.

Figure 1. A) Fluorescence emission spectra (λex = 470 nm, slit widths for excitation and emission: 5 nm) and B) photograph recorded immediately (unless otherwise stated) under irradiation at 365 nm by a UV lamp for micellar solutions of P(Si-co-NBDAE-co-SPA)$_{50}$-b-P(NIPAM-co-RhBAM)$_{30}$ under various conditions: a) pH 7 and 25°C; b) pH 3 and 25°C; c) pH 3 and 35°C; and d) pH 7 and 25°C upon UV irradiation for 2 min. C) Fluorescence emission spectra under the same conditions in the pH range 3–9.

Figure 2. A) Fluorescence intensity ratio changes $I_{RhBAM}/I_{NBDAE}$ as a function of temperature recorded for the micellar solution (pH 3) of P(Si-co-NBDAE-co-SPA)$_{50}$-b-P(NIPAM-co-RhBAM)$_{30}$. B) Time evolution of fluorescence spectra (conditions as before) recorded for the micellar solution (25°C and pH 7) upon UV (365 nm) irradiation.

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Figure 2a it follows that the diblock copolymer micelles can act as fluorescent ratiometric dual probes for pH and temperature. Moreover, the detection sensitivity of pH can be considerably enhanced at 35°C, relative to that at 25°C (Figure S15).

The presence of SPMA moieties in P(ST-co-NBDae-co-SPMA), b-P(NIPAM-co-RhBAM), diblock copolymer can add extra features to the modulation of multicolor emission. We further investigated the photoswitchable emission behavior of the diblock copolymer micelles at pH 7 and 25°C, under which conditions RhBAM moieties exhibit no fluorescence emission; thus, only the green emission from NBDae moieties can be observed under visible light (Figure 1B).

We observed the appearance of a new emission band at around 645 nm upon UV irradiation, the intensity of which gradually increased with irradiation time and stabilized after 1 min (Figure 2b and Figure S17 in the Supporting Information). Concomitantly, the NBDae emission intensity at 518 nm exhibits a dramatic decrease. This change indicates the occurrence of a FRET process between NBDae and the merocyanine form MCMA. Visual inspection of the micellar solution under a UV lamp (365 nm) revealed an abrupt green-to-red transition fluorescence enhancement (Figure 1B). It is notable that under UV irradiation at pH 7 and 25°C, RhBAM residues are stable and exist in the closed form, as evidenced from the control sample only containing NBDae and RhBAM dyes (Figure S18 in the Supporting Information), which might be ascribed to the chemical structure and the fact that RhBAM moieties are located in a hydrophile microenvironment.34 Upon five cycles of alternate UV and visible-light irradiation, the emission intensity at 645 nm can essentially recover to its original value (Figure S17 in the Supporting Information).

In conclusion, we demonstrated the first example of an amphiphilic responsive block copolymer micelle based multichromophore luminescent system exhibiting reversible three-state switching of fluorescence emission (green, yellow, orange, and red) by modulating two independent FRET processes by external stimuli (e.g., pH, temperature, and light irradiation). The reported diblock copolymer micelles can serve as sensitive ratiometric fluorescent dual probes to pH and temperature; moreover, the detection sensitivities can be facilely adjusted through thermo-induced collapse of responsive micellar coronas owing to the closer proximity between the FRET donors and acceptors. This novel type of multicolor luminescent polymeric assemblies augurs well for practical applications in cell imaging, biosensing, and clinical diagnosis.

**Experimental Section**

Experimental details, including the synthetic procedures, characterization methods, and all relevant characterization data, are available in the Supporting Information.

Preparation of micellar solutions: P(ST-co-NBDae-co-SPMA), b-P(NIPAM-co-RhBAM), (10 mg) was dissolved in N,N-dimethylformamide (DMF, 1 mL). Under vigorous stirring, deionized water (9 v/vL) was added through a syringe pump at a flow rate of 0.2 mL min⁻¹. After the addition was completed, the dispersion was left to stir for another 5 h. DMF was then removed by dialysis (MW cutoff, 14,000 Da) against deionized water for 24 h. Fresh deionized water was replaced approximately every 6 h. The micellar solution exhibited no macroscopic phase separation upon standing at room temperature for more than three months, suggesting the formation of stable micelles. All pH adjustments were made by adding aqueous HCl or NaOH.

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